POLITECNICO
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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Methodology for sustainability-oriented platform design for circuit breaking technologies

Tesi di Laurea Magistrale in
Mechanical Engineering - CM1: Digital Technologies for Product Development

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Academic Year: 2025-26

Abstract

Manufacturers of power generation, transmission, and distribution equipment such as switchgears and circuit breakers are required to meet high standards in terms of both products functionalities and how the products perform their functions. Historically, the optimization of quality requirements has been addressed by developing product platforms and finding their optimal extent. In the last years, the high demands of energy sector have called for an early integration of sustainability into the design process, in order to include it in the optimization of costs and performance. However, simultaneously optimizing multiple parameters requires that the requirements are precisely scaled and characterized since the early design stages, and this is critical for sustainability, because it lacks a standard measurement framework. For this reason, the present thesis proposes a methodology to integrate a comprehensive approach to sustainability since the early platform design development stages. The proposed methodology will address sustainability and quantify it early, by combining Lifecycle Assessment (LCA) analyses and the circularity strategies of 10Rs framework. This comprehensive approach to sustainability will allow the generation of sustainable solutions, that will be evaluated based on how they impact the other quality requirements. In this way, the methodology will serve as a decision-making support for designers, evaluating when it is convenient to implement a sustainable solution. The methods mainly used in the analysis are the Enhanced Functions-Means (EF-M) model and the Design Structure Matrix (DSM). The methodology has been applied to redesign an industrial Air Circuit Breaker (ACB) during a work-shadowing semester. The validation of the methodology has been performed through semi-structured interviews and weekly reviews with representatives of the manufacturing company.

Keywords: Product Platform Design, Sustainability, Enhanced Functions-Means Model, Design Structure Matrix

Abstract in lingua italiana

Alle aziende manifatturiere che si occupano di dispositivi per la produzione, trasmissione e distribuzione di energia elettrica come quadri elettrici e interruttori, viene richiesto di soddisfare alti standard per quanto riguarda sia le funzionalità di prodotto, che come queste vengono svolte. Storicamente, l'ottimizzazione dei requisiti di qualitatà veniva soddisfatta dallo sviluppo di piattaforme di prodotto e dall'ottimizzazione del numero delle loro varianti. Negli ultimi anni, le esigenze del settore energetico richiedono che la sostenibilità venga integrata sin dalle prime fasi della progettazione, e ottimizzata insieme a costi e performance. Tuttavia, ottimizzare contemporaneamente più discipline richiede che i requisiti siano precisamente caratterizzati e ne sia definito l'ordine di grandezza fin dalle prime fasi dello sviluppo di prodotto, e questo risulta complicato per il bisogno sostenibilità, che non è universalmente quantificabile. Per questo motivo, la presente tesi propone una metodologia per integrare i requisiti di sostenibilità e implementarli fin dalle prime fasi di sviluppo della piattaforma. La metodologia proposta affronterà e quantificherà la sostenibilità di prodotto servendosi di valutazioni dell'impatto ambientale (LCA) e delle strategie circolari delle 10R. Questo approccio comprensivo alla sostenibilità permetterà di generare soluzioni sostenibili, che verranno valutate rispetto ai benefici e svantaggi che portano agli altri requisiti di qualità. In questo modo, la metodologia servirà da supporto nel processo decisionale dei progettisti, valutando la convenienza nell'implementazione delle soluzioni sostenibili. I metodi maggiormente usati nell'analisi sono il modello Enhanced Functions-Means (EF-M) e la Design Structure Matrix (DSM). La metodologia è stata applicata per riprogettare un interruttore aperto (ACB) durante un semestre di affiancamento lavorativo. La validazione della metodologia è stata ottenuta conducendo interviste semi-strutturate e revisioni settimanali con i dipendenti dell'azienda produttrice.

Parole chiave: Progettazione Per Piattaforma, Sostenibilità, Enhanced Functions-Means Model, Design Structure Matrix

Contents

Introduction

To respond to a more pressing market industry, products in power transmission and distribution like switchgears and circuit breakers are expected to meet competitive benchmarks in terms of both functional capabilities and quality expectations [1]. In fact, aspects that are not linked to functionalities such as cost-effectiveness, high performance and compliance with regulations have become fundamental in determining consumers purchases and products success [2].

To satisfy these quality requirements, the manufacturers of these products have long relied on product platforms, sets of common elements (the platforms), shared among a product family, allowing manufacturers to increase cost-effectiveness and foster future scalability of the production line [3, 4]. For example, the company ABB has developed the Emax series, platforms of different Air Circuit Breakers (ACBs) with modular architectures, characterized by the same core configuration, and different variants in terms of size, breaking capacity and optional upgrade units (Figure 1).

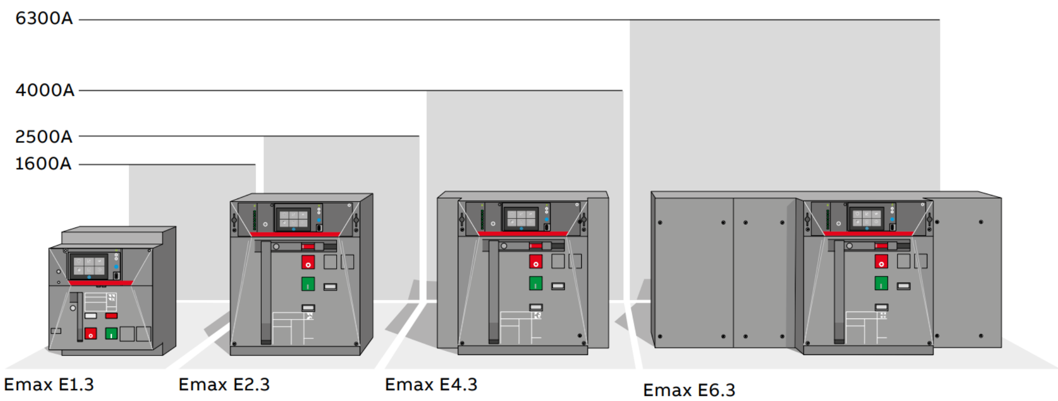


Figure 1: Different models of Emax3 platform, sorted by frame sizes and rated currents [5].

However, platforms must meet the requirements placed on all products in the family: if the optimization of products and families is not balanced, it results in a lack of customization and overdesign. In one of the Eckert et al. [6] examples, Volvo used two different cooling fans sizes for its trucks platform. If one specific model requires an intermediate size, the platform will impose to install the bigger fan, even if it is over-sized.

Platform optimization is most effective when performed at early design stages; for this reason, the aspects that are usually optimized in complex engineering product platform are costs, effort, and risks [7], all easily quantifiable. Emerging needs like sustainability are only considered subsequently, due to the difficulties to estimate their scale at the start of a design process [8]. However, sustainability will be the focus of the present methodology: this means that part of the methodology will be committed to evaluate the trade-offs among this parameter and the aspects linked to costs, compliance with regulations and performances.

At the moment, the interest for sustainable design [9] is spread across the whole industrial market, with a particular focus on the products used in the energy sector [10]. The companies belonging to this sector are heavily involved in the achievement of Sustainable Development Goals [11], but also subjected to strict regulations due to their substantial contribution to energy consumption and resource utilization. In particular, data centers and utilities currently lead the green transition [12], as they are major contributors to electricity demand and answer to dedicated regulations regarding energy efficiency [13], while smaller businesses struggle to implement sustainability strategies.

The approaches of product platform and sustainability share the same principle of resource sharing and processes' efficiency. Another common aspect is modularity, which is an approach to organizing complex products in simpler portions that can be managed independently or as a whole [14]. The degree to which a system's parts can be separated and recombined is largely governed by their inter-module dependencies, that can be both direct (given by physical constraints) or indirect, when they depend on customers' needs and requirements [15]. Product platforms rely on different modules combinations that increase products design variations [16], while for the sustainability side, modular architectures improve product disassembly and end-of-life management, by facilitating maintenance, repairability and recycling processes [17].

An everyday example of modular architectures are desktop Personal Computers, where core components such as the CPU, memory and graphics card can be independently upgraded or replaced without modifying the rest of the system. This is possible due to the standardization of their interfaces, which decouples hardware modules and also allows to add external modules such as keyboards, mice and monitors to the system [18].

Combining sustainability with modular platform design can foster resource utilization, processes' efficiency, modularity and economies of scale [4]. However, modular architec-

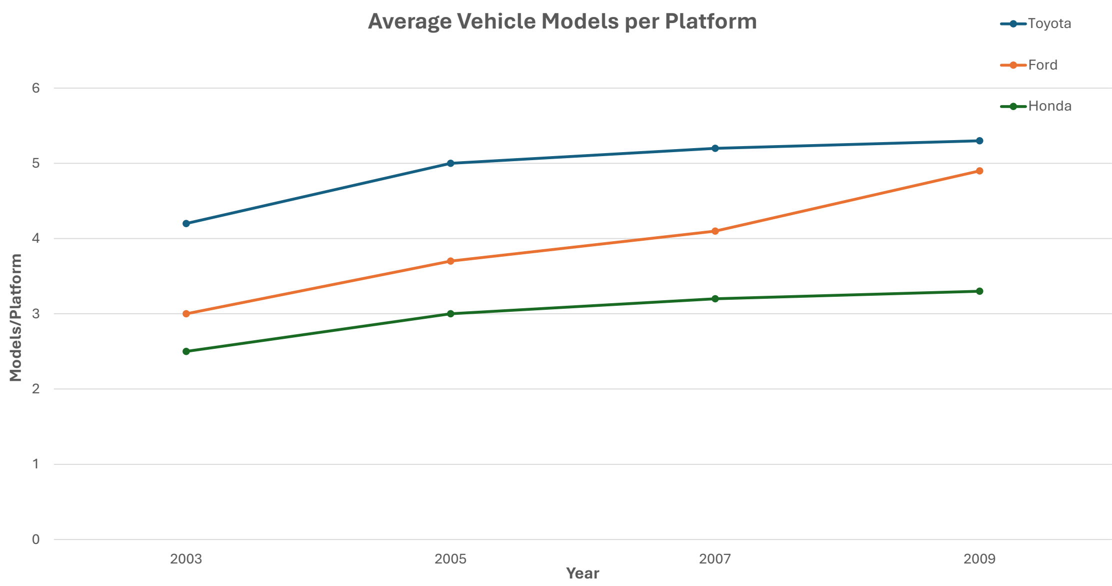


Figure 2: Simplified variants per platform trend in the automotive industry, adapted from De Weck [21].

tures usually increase products dimensions and complexity of their interfaces [19] and also implicate a trade-off among the need for sustainability, product functionalities and customers' expectation. For instance, Celona et al. [20] investigated the difference in the sizes of similar modular and integrated products, such as cell phones and desk phones, and laptops and desktop computers, finding that the modular counterparts had a larger size despite performing the same functions. This difference was due to the volume added to create compatible interfaces among their modules.

The simultaneous optimization of different aspects leads to the generations of multi-platforms (various extents of the same platform), resulting in the necessity to identify the optimal number of variants through measurable criteria. This concept is highlighted in De Weck's work [21], where the optimal number of platform variants for the automotive market of the first 2000s has been researched, answering to the increasing average number of models per platform. The growing trend of the number of models per platform for the brands Toyota, Ford and Honda is shown in Figure 2.

From these trends it is evident that sustainability will be included into platform design, but this will be critical for the optimization of the other disciplines, due to the difficulties in measuring and comparing these different aspects since early design stages. The objective of the present thesis is therefore to provide a methodology that will guide designers in the integration of sustainability strategies into product platform development, responding to the demands of the industrial market. To have an effective integration, a framework will be developed to guarantee a comprehensive approach to sustainability, combining LCA-based analyses and circularity strategies. The resultant methodology will also serve a decision-making support to define the optimal degree of sustainable solutions implementation compared to the other customers' needs. The case study chosen to illustrate this methodology is a series of Air Circuit Breakers (ACB), since they are fundamental elements of the electrical grid, that must withstand high safety and performance standards, and sustainability-oriented requirements such as material sustainability and energy efficiency.

1 | Research context

This chapter will focus on the context surrounding the methodology development, especially on the company ABB. In fact, the expected outcome is a methodology that will become part of ABB's ecodesign strategies and will help designers to combine sustainability and platform design. Finally, the content of the following chapters will be summarized, giving an excursus of the thesis' topics.

1.1. Context

Following global trends, major companies related to the energy sector are implementing different strategies to improve their approach to sustainability [22–29], and the present thesis will focus on one of them: ABB.

ABB is a global technology leader specialized in electrification, motion and automation. By connecting its engineering and digitalization expertise, ABB helps industries achieve high performance and become more efficient, productive and sustainable. For this reason, ABB's tagline is "Engineered to Outrun". Sustainability is one of the company's main purposes, and it is addressed starting from three fundamental pillars, as stated in the sustainability report 2025: "ABB's Sustainability Agenda aims to enable a low-carbon society[1], preserve resources and promote social progress" [22].

Resource preservation is ensured by the circularity assessment of their products against eight different key performance indicators (KPIs), with a focus on water consumption monitoring. Social progress is another pillar of the company vision, and it is addressed by a total commitment to workers well-being. This means promoting diversity and a correct work-life balance, while keeping the safety of the workers as an absolute priority. Finally, to increase transparency of their value chain, ABB provides third party's certified EPDs for each of its products, including retrofitting kit, easily accessible from their website[2].

The present thesis will be included in the landscape of new strategies implemented by the

[1] ABB is committed to adhere to the "Net Zero Emissions by 2050" scenario of the International Energy Agency (IEA)

[2] Link to ABB's public library of Environmental Product Declarations

company to achieve its sustainable ambitions, and will enable the integration of sustainability into platform development.

1.2. Expected Outcome

The expected result of the present thesis is a methodology that combines the principles of sustainability and platform design. This will serve as a decision-making support for designers, as it will highlight the trade-offs between sustainable and functional solutions, while enabling space for future changes.

The methodology will guide the designing phase both with and without a starting product. In the first case, the guidelines provided will lead designers to analyze the existing product under new lenses, and to have a clear understanding of what systems have the main environmental impact and what features can or cannot be compromised to enhance their sustainability. In the absence of a starting product, the engineers will directly proceed to identify market requirements and will be guided to their integration into a design space, that will underline the sustainable potential of their ideas. In the final phases, designers will be given the tools to compare different product architectures and evaluate them according to the functionalities, to fulfill the previously identified requirements.

In the absence of the present methodology, designers could still implement platform and ecodesign individually, but the two approaches would generate different product architectures, and they would need an ulterior analysis to merge them into what the market is requesting. However, by following the methodology, engineers will find a sequence of codified steps that will guide them to integrate sustainability and platform design effortlessly, and a set of parameters that will evaluate their results.

1.3. Structure

The present thesis is structured as follows.

First, Chapter 2 will discuss some of the contemporary research on platform design and sustainability. As it will be shown, the two subjects evolved independently, and their integration in the academic literature is recent, providing the academic gap of the thesis. In fact, its main objective is to integrate the topic of environmental sustainability and platform design in a single methodology, whose steps are clear and intuitive for designers.

It will follow a dive in the research activity performed to develop the methodology and in the steps who compose it. The methodology will start by analyzing the architecture of a starting product (if present) and identifying its main functional blocks. After this step (or in the absence of a starting product) a market analysis will be conducted to research functional and non-functional requirements. The next phase will present the mapping between the product systems and their relevance to the fulfillment of sustainability requirements, and the hotspots will be analyzed in detail to find any opportunity of enhancing their sustainability. Any alternative solution to the components, interfaces or processes that have the most environmental impact will be listed and later evaluated based on the initial requirements. The solutions that will satisfy more requirements will constitute the new product architecture, ready to be further analyzed to find other opportunities for improvement.

Chapter 5 will then show the methodology applied to the real case of a circuit breaker series: ABB's Emax3. This high-performance innovative product will be broken down to its most essential functional blocks and rebuild under the lenses of a more sustainable architecture.

The result of this operation of deconstruction and rebuilding will be discussed in order to assess the present methodology's validity and limitations in Chapter 6. Possible future developments and work prosecution will also be presented, such as an increased automatization of the manual operations through the implementation of AI algorithms.

2 | State of the art

This chapter will illustrate the state of the art for the topics of product platform design and sustainability. It will start with a literature research of the theoretical foundations of the topics and will continue by presenting different methods used to represent product functional architecture, which are needed to show the methodology approach. Besides, the research gap will be highlighted and it will be shown where the methodology will position in the academic research. Finally, the thesis' objective will be presented and explained.

2.1. Product platforms

Platform design was first addressed in the 90s, to support products mass customization and reduce development costs through the adoption of modular architectures [30]. The methodology consists in creating complex systems by combining independent, interchangeable, and standardize modules, onto a shared foundation [31]. By reusing design knowledge and physical components across a product family, product platforms can improve development efficiency and reduce time-to-market [32]. From an innovation perspective, platform design focuses on product architectural changes, rather than incremental or radical innovations, that is the reorganization of existing product systems, without changing their components [33].

The frameworks to develop a product platform usually start with the analysis of market needs and the identification of customers' requirements [3]. This preliminary phase is necessary to characterize the product uncompromisable functionalities. Based on these requirements, a design space where all the platform variants can coexist at the same time is designed [30]. Here, different design solutions satisfying the requirements are generated and added to the space, creating different versions of the same platform [4].

The generation of alternative components is ruled by the definition of boundaries, that partition the platform into different modules and assign them to particular requirements and functionalities [6]. At this point, the modules that are common for every configuration will constitute the platform core, while variable modules will be the base for product differentiation and platform extension. To define products architectures, the interfaces and interactions among modules are defined to ensure compatibility among them [4].

The final step of platform development is the evaluation activity. Since platform development usually results in more than one optimal solution, this is the phase where trade-offs among results are considered, in order to define the optimal platform extent [30].

Sudjianto and Otto [34] presented a practical example of this process, by developing a platform for power tools belonging to different brands of the same company: Black and Decker's DeWalt, Firestorm, Quantum and VersaPak. The customers' requirements analysis illustrated that DeWalt customers prioritized performance and robustness, VersaPak users focused on affordability and versatility, and Firestorm customers sought higher performances. The aesthetics characterizing each brand were analyzed as well. At this point, the variants in the products designs were added to a family function structure, where alternative design solutions such as power output, battery capacity, housing design, and aesthetic features were explored. To define the product architectures, common and alternative solutions were partition into different modules using the modularity matrix (Figure 2.1). Starting from this matrix, common modules like motors, batteries and transmission systems constituted the core platform architecture and the compatibility between the common and alternative modules was ensured. Finally, alternative platform configurations were evaluated by balancing the economic advantage obtained through component sharing against the need for market differentiation.

Product platform design offers the advantages of enhancing products flexibility and adaptation to evolving market demands. In addition, the adoption of platforms reduces manufacturing complexity and production costs [35]. Nevertheless, product platforms are optimized for a whole family of products, rather than individual products. This often limits opportunities of customization and sometimes lead to the overdesign of simple variants of the family [6, 7]. For this reason, architecture definition is one of the most crucial phases for platform development.

Moreover, platform design becomes difficult when there are multiple discipline involved, and this is the case for the products involved in power transmission and distribution, like ABB's products. In this case, to understand what are the best alternative solutions, platform design is supported by Multidisciplinary Analysis (MDA) [36], that evaluates complex systems across different parameters. For this reason, it is necessary to determine the right extent of the platform and choosing carefully the aspects to optimize.

	FIRESTORM	Quantum	DEWALT	VERSAPAK
Dominant theme	High performance	High value	Heavy duty	Multi-purpose
Transmit power	Shaft	Shaft	Shaft	Shaft
Input signal	Trigger	Trigger	Trigger	Trigger
Switch power	Variable Speed	Variable Speed	Variable Speed	2 Speed
Encase color	Red	Green	Yellow	Blue

Core platform module

Brand specific module

Figure 2.1: Simplified Circular Saw Family Modularity Matrix, adapted from Sudjianto and Otto [34].

2.2. Product architecture representation and modeling approaches

The academic world offers various example of methods and tools to implement platform design [9]. Although each one of these methods can be implemented manually, in the last years, the focus moved on digital tools and benefits they bring to sustainable design practices [37]. For this reason, this section presents an analysis of models that connects requirements and design solutions to implement platform and sustainability design.

The models to represent products architecture in platforms development are usually based on product functions, modularity drivers and/or systems' structure [38].

The functions heuristics methods are based on customers' needs, that are analyzed to extract the functions that the products must perform. During the implementation of this type of methods, the products systems are partitioned and reorganized in functional flows to emphasize their purposes [39]. This type of models fosters platforms development, however it lacks the possibility to include technical solutions associated to the functionalities. Modular Function Deployment (MFD) on the other hand, is a consolidated method for developing modular products that starts identifying customers' requirements and associating them with technical solutions [40]. However, MFD limits flexibility and could affect the creativity behind the generation of sustainable solutions.

To overcome the limitations imposed by heuristics and MFD methods, the present thesis will focus on the Enhanced Functions-Means models (EF-M) to portray the relationships among product components (the so-called Design Solutions DS), their Functional Requirements (FR) and Constraints (C) [41]. The EF-M method however, does not represent the interactions among the product subsystems. This is why the present methodology will integrate it with the Design Structure Matrix (DSM) method. The DSM is a method based on product systems' structure, and is a popular design tool used to map the interactions among products subsystems [42]. Allowing designers to identify clustered modules, DSM enables both platform design and sustainability. However, DSM alone represents neither the logical link between the product and its functions nor customers' requirements, for this reason it will be used in conjuction with EF-M.

2.2.1. Enhanced Functions-Means Model

The Functions-Means (F-M) method was born in the 90s to complete design information provided by CAD models. In fact, CAD models describe the physical embodiment of products, like geometry and dimensions, but do not represent the rationale behind choices or functionalities. The F-M model was therefore introduced to capture the logical and functional structure of products [43].

The F-M model provides an abstract product representation that models the function performed by the subsystems without explicating the product geometry. As shown in Figure 2.2, the F-M model has a hierarchical tree structure, where a product is decomposed in its components, each of them answering a specific Functional Requirement (FR). In this design space, the product subsystems are called Design Solutions (DS) [41] and each of them is linked to a function. The tree structure is given by the fact that every DS can generate additional sub-functions that are iteratively satisfied by other sub-solutions. This operation can be repeated until achieving the desired level of detail in the product architecture.

To enrich the information provided by the F-M model and adding flexibility, some product Constraints (C) can be added to the tree. These constraints represent modeling dependencies, incompatibilities and design limitations, allowing the model to represent feasible design spaces. In this way, the F-M becomes an Enhanced Functions-Means (EF-M) models. The strength of EF-M models is the possibility of generating alternative DSs disconnected from product geometry, thus fostering creativity and exploratory design, by grouping multiple DSs to the same function at the same time [44]. This is possible by moving from axiomatic designs (where each FR is satisfied by a single DS) to an exploration space, where different alternatives DS are linked to the same FR and constitute different product architectures [45].

Besides, the DSs of the lowest means of the EF-M model can be translated into a Design Structure Matrix (DSM), which can be used for the product structure analysis. As a matter of fact, the DSM highlights components interactions and architectural coupling, supporting platform development. For what concerns platform design, the simultaneous use of the Enhanced Functions-Means (EF-M) tree models and DSMs allows designers to simulate changes in platform architecture, by emphasizing the interfaces involved in such changes [45].

2.2.2. Design Structure Matrix

The Design Structure Matrix first appeared in the 80s to simplify the management of interdependent variables in complex systems and simplify design iterations and reviews [46]. Today, the DSM remains a popular design tool due to its simplicity and conciseness [42], and represents the focus of the present methodology.

The DSM consists in a square matrix where the diagonal cells represent the product components or subsystems, while the off-diagonal cells show the dependencies, interfaces and interactions among the elements [42]. The structure of the DSM can be modified based on the type of relationships to emphasize, but the present thesis will consider the DSM shown in Figure 2.2 as base structure, with the following types of interactions among subsystems:

- Spatial: for the subsystems must be in a certain reciprocal position to interact and perform their function.
- Information: for the subsystems that communicate with each other through signals or information.
- Energy: for the subsystems which exchange energy.
- Material: for the subsystems which exchange material.

DSMs can be adapted to show direction of interaction (for instance if the information always flow from component A to B and not vice versa) and even their magnitude (for example if component A and B exchange energy). However, this type of detail is not required for the present thesis, that will consider each of the interactions type bidirectional and without any magnitude, while referring at Eppinger and Browning [47] for a deeper

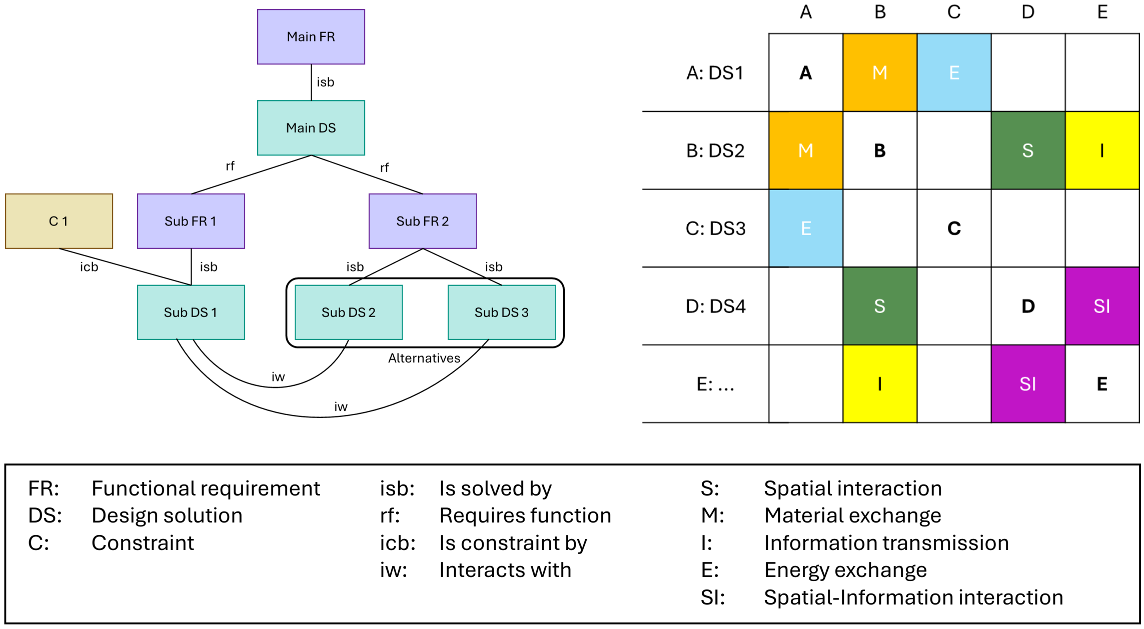


Figure 2.2: Base structure of an EF-M model (adapted from Levandowski et al. [48]) and a DSM, explained.

dive on the topic.

From the sustainability side, DSM emphasizes opportunities for modular design, by highlighting systems clustering opportunities [47], hence facilitating disassembly and end-of-life processes as recycling. Furthermore, DSM can be expanded and rearranged to collect environmental indicators, constituting an early environmental assessment of industrial products [49–51]. For example, the main diagonal, which refers to a single component, hence it is not used to show interactions, can be used to display the emissions generated by the component in terms of Global Warming Potential (GWP), energy consumption, recyclability fraction or other environmental indicators. Also, columns can be added to note sustainability issues or particular regulations to consider from the design phase to iteratively improve the design.

2.3. Functional and Non-Functional Requirements

In the market analysis performed during platform development [4, 52], the parameters that will become MDA objectives are collected through interviews and benchmark researches. However, the raw information deriving from them may be qualitative and subjective, namely the customers' needs, and usually need to be reformulated. The necessary reformulation into formalized and structured information, made of metrics and values, to measure the fulfillment of the corresponding need, translate them into requirements [53].

Correctly identifying and satisfying the correct requirements is essential especially in the energy sector, where the customers are highly informed and demanding about products specifications. This awareness comes from the business model adopted in the field, B2B, acronym for "Business to Business". This consists of all organizations that purchase goods or services used in the production of other products that are sold, rented or provided to other consumers [54].

To efficiently satisfy the energy market segment, Non-functional Requirements (NFRs) must be integrated into MDA of platforms, as well as the Functional ones (FRs), namely the requirements that describe the behavioral aspects of a system and constitute functions that the product must be able to perform. In contrast, the NFRs describe how the system will accomplish its goals, rather than how it will perform [2].

To understand the difference, Shankar et al. (2020) provides a clear example from the automotive industry, a cost-effective reinforcement for a rear-bumper [55]. FRs, such as the imposition of bumper bracing to resist deformation from impacts, focus on a single action type aspect of the product, while NFRs as the 10-years durability, the manufacturing carry-over or even sustainability (not present in the mentioned study) require some knowledge about the whole product and it is more difficult to quantify.

Despite the challenges of measuring the NFRs, relevant studies show the positive influence of their integration in products' early design phase [56, 57]: a notable example is Forti et al. [58] study, where NFRs were used to guide the integration between the modularization methods of Design Structure Matrix (DSM) and Modular Function Deployment (MFD) in the automotive sector. Here, the interactions among subsystems represented in the DSM were combined with the MFD Module Indication Matrix (MIM) (Figure 2.3), which associated requirements as maintainability, carry-over and recyclability to the technical solutions through a correlation score[1] of 1, 3 or 9. In this way, NFRs served as modularity drivers, complementing DSM to highlight clustering opportunities.

It is therefore fundamental to consider NFRs during platform development, as they set the modules' architecture and inter-dependencies. In this way, NFRs start to actively participate in the design definition, highlighting clusterization opportunities and becoming modularity drivers.

[1] This scoring system is widely used in MFD and will be the base for the evaluation activity proposed by the present methodology.

		NFRs serving as modularity drivers				
		Carry-over	Maintainability	Units commonality	Upgradability	Recyclability
Technical solutions	Axle housing	9				3
	Axle shaft	9				3
	Carrier set		9			
	Wheel hub set	9	3	9		3
	Drum brake					3
	Brake chamber		9		1	
	...					

Figure 2.3: Simplified Module Indication Matrix (MIM), adapted from Forti et al. [58]. The figure shows the link among NFRs (modularity drivers) and technical solutions with scores of 1, 3 or 9, depending on the intensity of the relation.

2.4. Sustainability: an emerging Non-Functional Requirement

Sustainability is interpreted as a NFR in engineering design, since it influences systems architecture, by imposing constraints on materials selection, energy consumption, durability and end-of-life treatments of products.

The first concerns about the environment and the finite number resources date back to the 60s [59]. Since then, the relevance of sustainability kept increasing and involving more research fields, such as engineering design. In fact, in the 70s sustainability was included in product design, with the development of Lifecycle Assessment (LCA) analysis [60]. This analysis first aimed at computing products emission loadings, and then evolved to consider their environmental impact during the whole lifecycle. This led to the development of ecodesign in the first 90s, an approach to include environmental requirements into the product development process [61]. The implementation of ecodesign allowed designers to measure the environmental impact of products throughout their whole lifecycle [62] through the computation of LCA.

Since the 90s, LCA is the base to a third party verified certification, required by various customers in the energy sector, the Environmental Product Declaration (EPD) [63]. These analyses are ruled by the ISO standard 14040:2006 and aim at quantifying the environmental impact of the lifecycle of a product, typically for the manufacturing, distribution, installation, use and end-of-life phases. In LCA analysis, the physical flows of energy and materials linked to the product lifecycle are translated into multiple impact categories. The most used indicator is the Global Warming Potential (GWP), that measures the product contribution to climate change in kilograms of CO_2 equivalent. However, LCA analyses provide valuable insights about Acidification Potential (AP), Ozone Depletion Potential (ODP), Human Toxicity Potential (HTP), Water Scarcity and many other environmental indicators.

Even though today LCA analyses are integrated into the early phases of product design, as opposed to limit their use to a comparison of products on the market [64], they still present some limitations. For instance, the datasets used to estimate impact of the manufacturing phase are often incomplete, as they require precise information about the material sources and the energy mix used in a particular geographic area [65]. Moreover, this type of analysis lacks consideration for use and end-of-life of products, as considers lifecycles as linear systems [62], they do not account for eventual parts failure and substitutions and they do not reward second-life products prospects, leaving a substantial part of sustainable strategies underrecognized [66].

In the 2010s, researchers tried to overcome LCA-based analysis limitations, by developing frameworks which consider lifetime extensions perspective from the early design phases [67]. These frameworks involve the so-called circularity strategies [68] and focus on the maximization of resource utilization, by adopting circular strategies to extend products lifetime since their design. The first circular framework was constituted by 3Rs, that stand for Reduce, Reuse and Recycle, but in the last years other strategies joint to reach the current 10Rs framework, explained in Figure 2.4. Even though these strategies lead to a better management of resources and a reduction in waste creation [69], they are not standardized as LCA [70] and do not provide information about energy management, making it necessary to still consider LCA-based analysis [71].

Sustainability is not only an assessment activity but a design requirement to integrate in the early stage of the product architecture definition. For what concerns how to integrate it, the literature offers various example: from the green design of a circuit breaker using resource optimization techniques [73], to the circular design of a tiny house and the issues deriving from it [70] or the Reuse framework applied to bicycle frames [74].

The present thesis, however, will illustrate a methodology that approaches sustainability through LCA-based analyses and the circularity framework of 10Rs, to obtain a comprehensive take on the subject during the early design phase, and weights the benefits of sustainable solutions compared on the other NFRs' satisfaction.

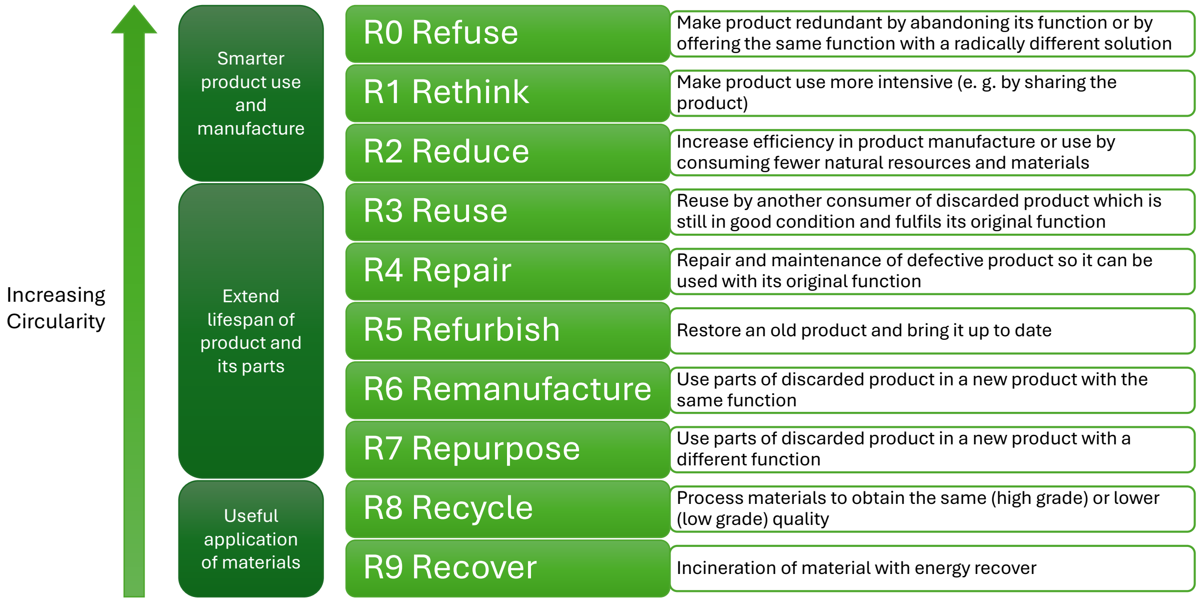


Figure 2.4: The 10Rs frameworks of circularity, explained. Image adapted from Muñoz et al. [72].

2.5. Research gap

Platforms and sustainability design developed independently until the mid of 2010s, when integration of the two topics started. In 2016, Wang et al. proposed a method to assign an instability index to components with the most impact on sustainability [75]. In the same year, Kim and Moon published a methodology that identified sustainable platforms for existing products family and integrated sustainability indicators in the decision-making process [76]. In 2017 the two academics introduced a multi-objective design optimization of the three sides of sustainability: environmental, economics and social, this time integrating the possibility to share some remanufactured modules in the product family [77]. Wang et al. focused on the topic of low-carbon design for product families in 2018-19 [78, 79] and started to include remanufactured products in the early stages of product families design as well, with the objective to reduce greenhouse gases (GHG) emissions.

Other works on the subject of sustainable platforms are presented by Shamsuzzoha and Helo and Zou et al.: Shamsuzzoha and Helo provided guidelines to find the optimal number of products variants for a sustainable platform in 2017 [80], while in 2024, Zou et al. focused on the energy consumption of assembly and disassembly processes in product families [81].

One of the reasons behind the limited integration of sustainability into platform design is the difficulty of including it in Multidisciplinary Design, Analysis (MDA) and Optimization (MDO) during the early design stages. MDA and MDO are used to support platform development by enabling the evaluation and balancing of multiple design objectives. However, their difficulties in the early design implementation are due to the common necessity of comparing criteria characterized by different units, when it is still critical to quantify them [82].

MDO in particular consists in a simultaneous optimization of different engineering domains, to identify the Pareto-optimal alternatives, and requires that costs and performances are expressed by consistent quantitative metrics [83]. In contrast, the need for sustainability is usually considered subsequently, due to the difficulties to quantify it comprehensively at early design stages [84]. Despite the potential of an early implementation of MDO addressed to performance, manufacturability and sustainability [8], the framework is still challenging to integrate in the platform architecture definition stage. Since MDO requires detailed information and provides a single optimal balance among parameters, the present thesis will use MDA-based frameworks to analyze and evaluate sustainable design alternatives against the other stakeholders' NFRs, obtaining multiple optimal balances for different ranges of customers.

The objective of the present thesis is to contribute to the integration of the topics of MDA of product platforms and the implementation of sustainability strategies (Figure 2.5) since the early design stages. This is possible, by providing a methodology that employs both LCA analyses and 10Rs circularity strategies to quantify the component with the highest environmental impact and the highest potential for redesign. This combined approach to sustainability is a novelty in sustainability-oriented platforms development methodologies and will emphasize the implementation of lifetime extension strategies from the start of the design process.

Another objective of the proposed methodology is to provide a comprehensive analysis of the trade-off between sustainability and the other requirements, both Functional and Non-Functional, in order to generate Design Solutions that are both sustainable and feasible in terms of technologies, costs and regulations. Even though the trade-off among different requirements has already been addressed [85], the present thesis will center the methodology around sustainability from the early design stage, instead of treating it as the other NFRs.

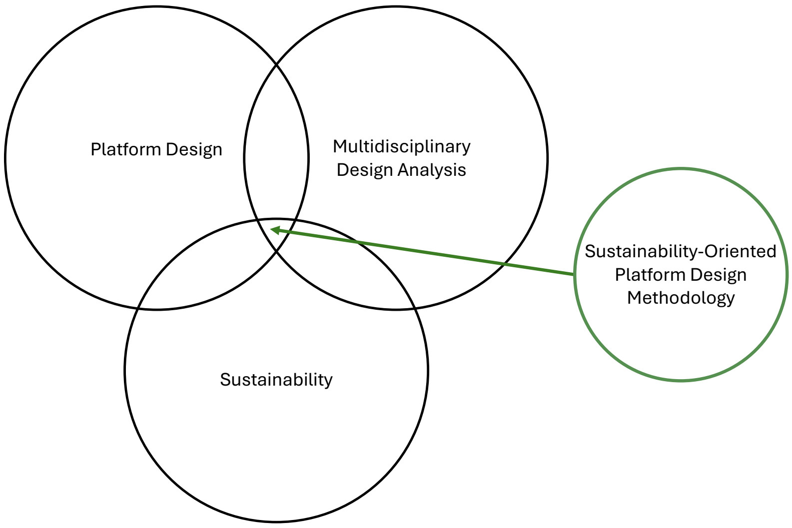


Figure 2.5: Representation of the present methodology position among the subjects of platform design, sustainability and MDA.

2.6. Thesis objective

The objective of the present thesis is to provide clear guidelines for the development of a sustainability-oriented product platform, used to redesign an existing product with an approach to sustainability or to design a new sustainable product platform.

The methodology will ensure the inclusion of sustainability NFRs since the early phases of platform development through an integrated approach, considering both consolidated LCA-based analyses and emission computations and the emerging circularity framework of 10Rs. The need for sustainability will guide the generation of new design solutions to reorganize the architecture of the product (or to constitute the architecture of a new product). The new solutions will constitute alternatives to the current product architecture, derived form the identification of product systems with the highest environmental impact and the highest potential for sustainable redesign.

In the sustainable solutions generation phase, FRs will be considered to assure their feasibility, while the other NFRs will be the base for the alternative solutions evaluation. In this way, the present methodology will highlight the trade-off between sustainability and the other NFRs, serving as a decision-making tool and estimating when it is profitable to implement sustainable solutions.

The obtained methodology will be later integrated into ABB's strategies to increase the sustainability of the company products.

3 | Research methodology

This chapter will illustrate how the methodology proposed by the present thesis to develop a sustainability-oriented product platform was formulated and put into practice.

3.1. Research activity

The research activity to build a methodology for the development of a sustainability-oriented platform involved case study research on a real industrial product. This consists in an empirical method used to investigate a specific phenomenon within its context and it is particularly suitable for validating methodologies involving complex products, which strongly depend on their environment [86]. The objective of the research was the definition of a methodology to integrate sustainability strategies from the early stages of platform development of a product belonging to the energy sector.

The environment for the case study research is the company ABB, where a low voltage[1] Air Circuit Breaker (ACB) was selected as case study. This is an essential element of the electrical grid, but also has a huge environmental impact. Moreover, the chosen product is high-quality and is already optimized in terms of performance, so that even a slightly emissions reduction will prove the validity of the methodology.

The research was performed during eight months of work-shadowing activity [88] in the R&D department of ABB SACE's headquarter. During this period of time, a qualitative observation of the company activities has been performed, to collect detailed information about ABB's strategies, processes and decisions-making frameworks, that it would have been difficult to obtain from outside the company. This approach allowed to analyze the existing product architecture and requirements, searching technical documentation and conducting interviews with employees. These operations were followed by the identification of the sustainability drivers and the generation of sustainability solutions. Finally,

[1]According to standard IEC 60947, circuit breakers are considered low voltage when they are are intended for circuits with rated voltages below 1000 V in alternating current (AC) or 1500 V in direct current (DC) [87]. The reference breaker is low voltage, even though it operates at 440 or 690 V, depending on the model, which is a higher voltage compared to residential installations.

the solutions were evaluated through qualitative and quantitative analysis, and a new platform architecture was developed.

The research quality and validity of the methodology was evaluated throughout the semester through weekly reviews and a final analysis of strong and weak points, and the possible future developments.

3.2. Case study research

Design research's purpose is increasing the chances of designing successful products [89]. This discipline relies on both technical and social sciences, therefore the methods supporting it must take into consideration functional aspects, as well as human and economic ones [90].

When the products to design are complex and heavily influenced by their setting, design research is supported by the case study approach, where a specific phenomenon or, in this case, a product is investigated in depth, along with the interaction with its natural setting [91]. For the case of a sustainability-oriented platform methodology, this research is particularly suitable because the methodology presented is strongly dependent by technical requirements, company practices, sustainability objectives, manufacturing constraints and market considerations simultaneously [86].

Experimental activities and case study research are classified as distinct research strategies within empirical investigation approaches. While experiments are centered around repeatability and systems responses under controlled conditions, case study allows to acquire a comprehensive knowledge about a research object, in this case a product, and the context where it belongs [86]. In contrast to the experimental one, this type of approach does not need a large sample of products and experiments repetition, as its purpose is to support decision-making process during product platform development and not to formulate universal theories [92]. To ensure the validity and repeatability of case study research despite the limited number of observations, multiple sources of structured evidence are used (interviews, documentation, observations...), a case study protocol is is developed and a case study database is maintained, to enable other researchers to trace and replicate the procedure [86].

3.3. Research environment

The case study research validating this methodology has been performed in ABB SACE headquarter. Here is located the R&D department of ABB's Electrification Smart Power division, which handles energy distribution and smart industries. Some of the productions leading the Smart Power division are low voltage systems, switchgears and breakers operating within the electrical grid.

Circuit breakers protect the electrical grid, by carrying current during normal operation and interrupting it when a fault is detected. In low voltage breakers normal operations, the current passes in a circuit closed by two contacts. When a fault is detected by the trip unit, the ruler of the breakers operations, the operating mechanism is released to separate the contacts, opening the circuit. The current interruption causes the generation of an electric arc, which is later extinguished by a system called arc chute.

The breakers where all the functional components are closely packed into molded insulating case are called Molded Case Circuit Breakers (MCCB), they are compact devices and typically interrupt lower rating currents. However, the present thesis will focus on Air Circuit Breakers (ACBs), which use a larger operating mechanism with stored-energy springs to open and close the contacts rapidly. The greater contact separation and larger arc chute allow them to interrupt much higher fault currents (Figure 1). For this reason, they are usually installed in large industrial plants.

The case study selected for this research is Emax3, the new series of ABB's ACB , designed to protect the circuits of critical power distribution systems such as data centers, utilities, industrial plants and infrastructure applications. This breaker is equipped with the latest electronics in order to offer high performance and reliability, other than advanced security [93]. Moreover, Emax3 already presents some sustainability solutions, like EPD certifications and a partial modular architecture, since its main subsystems are distinct modules that can be upgraded or substituted without changing the whole breaker. However, the current configuration is optimized in terms of performance, and a platform-oriented sustainability analysis of the product could help reducing its environmental impact.

The choice of the case study went to a very high quality product in order to illustrate the validity of the methodology. Developing a sustainability-oriented platform for Emax3 is a challenge, because the product is already optimized to offer the maximum performance. However, analyzing it from a sustainable point of view may result in new design solutions, and their trade-offs with functionalities and other NFRs will be analyzed and evaluated.

3.4. Data collection and analysis

To collect the necessary data to develop a sustainability-oriented platform for Emax3, a work-shadowing activity was performed in ABB SACE headquarter in Bergamo (Italy).

The activity lasted from November 2025 to June 2026 and guaranteed open access to the company documentation.

The primary source of information were about ten among catalogs and technical documentation. For the sustainability hotspots identification, the Bill of Materials (BOM) and detailed LCA-analyses of the product were particularly useful, by providing quantitative data about the breaker's weight, material composition and environmental impact. Moreover, functional models of the product, catalogs and assembly instructions were essential in understanding the structure of the breaker and its functionalities.

Complementary to this research, eighteen semi-structured interviews have been conducted throughout the whole time lapse. This is an effective data collection approach, that employs closed, open-ended and follow-up questions and lasts below an hour of time [94]. Even though the interviews take a considerable amount of time, since they are performed with one interviewee at a time and need time to be prepared and subsequently analyzed, their flexibility allow to examine in-depth products qualitative aspects, workers considerations, and even to change the focus of the interview.

The topics faced during these meetings were company customers' characterization, NFRs identification, sustainability of products and their materials, maintenance strategies and circularity, and energy efficiency. The interviews lasted from 20 to 50 minutes, with an average of 32 minutes each. The people interviewed are a R&D Executive Engineer, a Senior Principal Engineer, five Product Managers, two Sustainability Leaders and Coordinators and nine R&D Engineers of the Electrification Smart Power division and their experience in the electrification business varies from two to twenty-nine years.

3.5. Research quality and validity

The research progresses were monitored and evaluated both throughout the whole methodology development thanks to weekly reviews of 40 minutes each. The involved reviewers are the R&D Senior Architect Lead and Innovation Manager, and the CoE (Centre of Excellence) LCA and EcoDesign Leader, with an experience of respectively twenty-six and nineteen years in the company and in the electrification business.

The methodology is verified when the DSs that satisfy the identified NFRs are found. However, there is no guarantee that the solutions satisfy the initial needs as well. This is the reason why an additional methodology validation is needed, where both the results and the process to arrive there are analyzed and evaluated.

During these reviews, work progresses were highlighted and discussed together, and at the end of the work-shadowing time span, a questionnaire was computed to assess the methodology's strong and weak points and the future challenges.

4 | Methodology for sustainability-oriented platform design for circuit breaking technologies

This chapter will present a detailed breakdown of the phases that constitute the methodologies for sustainability-oriented platform development. These are the Preliminary Phase, the Requirements Identification, the Components-Sustainability Mapping, the Solutions Generation and Evaluation, and the Product Architecture Analysis.

4.1. Methodology introduction

The methodology to develop a sustainability-oriented platform requires the architecture of the product that is object of the redesign or, in case there is not any starting product, the idea of the general architecture of a new project, and a general customers characterization. After guiding designers in the computation of product's EF-M models and DSMs, and in the research of stakeholders requirements, a new product platform architecture is generated and evaluated, representing the output of the process.

The methodology is made of five essential steps (Figure 4.1):

0. Preliminary Phase: this phase requires as input general knowledge about the product architecture and the uncompromisable functions of its main subsystems. The outputs generated will be a EF-M model of the product and relative DSM.
1. Requirements Identification requires information about customers and stakeholders expectations regarding the product NFRs. These can be collected through interviews and benchmark researches and lead to a requirements priority matrix and a market segmentation for the different ranges of customers. Once identified the sustainability-oriented NFRs, they are added to the product EF-M model as inde-

pendent functions.

2. Components-Sustainability Mapping: the inputs for this stage are environmental information about the product, in particular how subsystems are linked to the satisfaction of sustainability-oriented NFRs. For instance, the impact of producing the materials that compose it, the expected lifetime of the subsystem and how they are disposed. The result of this phase is the identification of components that are sustainability hotspots in the product EF-M model.

3. Sustainable Solutions Generation phase starts generating design solutions that satisfy the sustainability-oriented NFRs added to the EF-M model, by suggesting changes or substitutions of the components that are hotspots for sustainability. The output will be an EF-M model presenting all the alternative solutions and as many DSMs as are the possible combinations of alternative design solutions.

4. Alternative Solutions Evaluation: this phase will receive as inputs the priority matrix resulting from Phase 1 and the alternative solutions generated in Phase 3. After assigning correlation scores to alternative solutions and stakeholders NFRs in the evaluation grid, this step will produce the ranking of all the possible DSMs for each range of customers, therefore pointing at the most suitable product architectures.

5. Product Architecture Analysis phase analyzes the highest-ranked DSMs found in Phase 4 to find the solutions alternatives that will satisfy more customers ranges, defining the optimal platform extent, and studies how to integrate the new solutions in the product architecture. The resulting new architecture will be analyzed again based on the evaluation grid computed in Phase 4, to find the NFRs that could be damaged by the introduction of sustainable solution and, eventually, restart the methodology loop.

The enabling tools used to implement the methodology are Trinity Systems Modeling[1] [44] for what concerns EF-M models and DSMs computation, Excel to manage customers' requirements and Visual Studio to evaluate DSs and rank the DSMs.

A small component of an ACB, the right plate for accessories (Figure 4.2), has been chosen to serve as significant example to illustrate the methodology, because it is an essential component, which is frequently substituted within breaker's lifespan. The right plate for accessories (often shorten in right MID, acronym for Mechanical Interface Design) is part of the ACB accessory module and serves as information bridge between the operating coils (the components that enable the opening and closing breaker operations) and the

[1] Julian Martinsson Bonde's Trinity Systems Modeling homepage

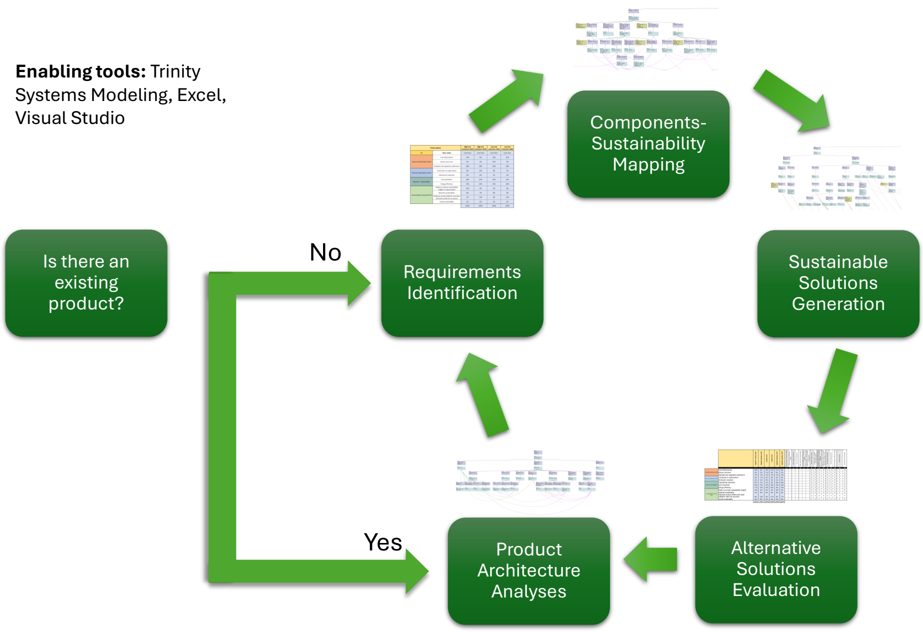


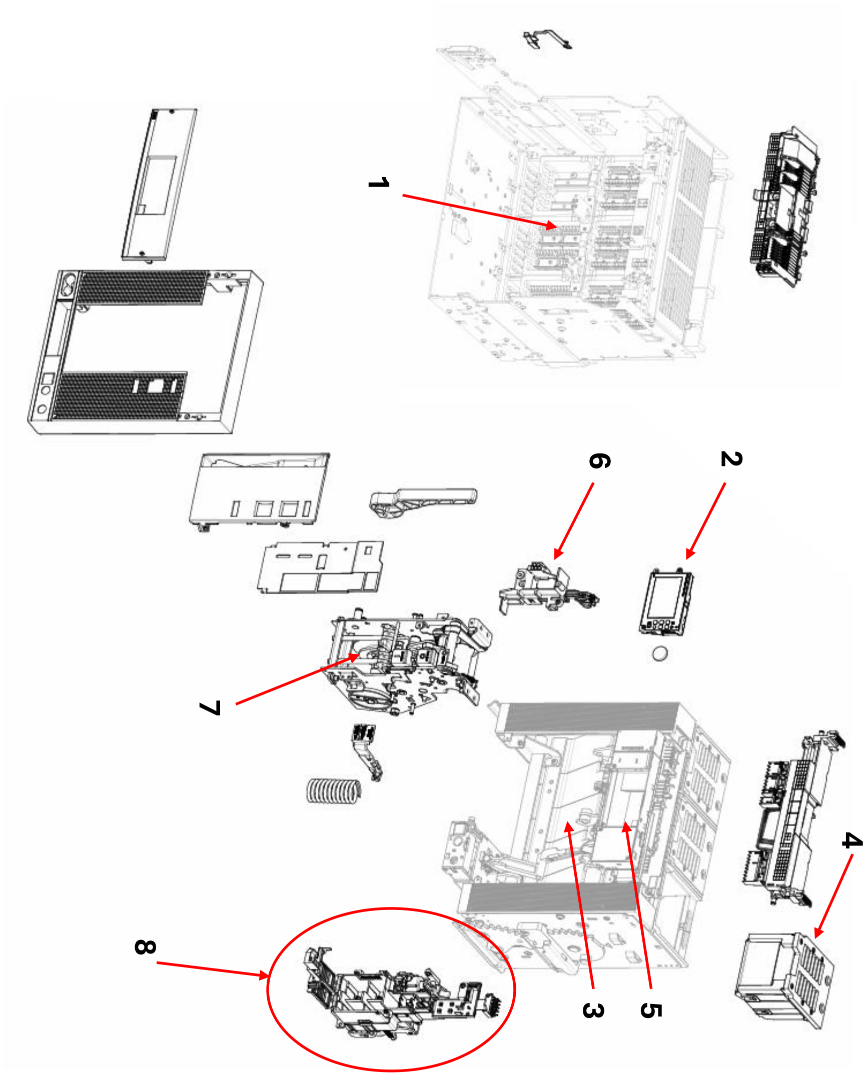
Figure 4.1: The Methodology Phases.

trip unit (the ruler of the breaker electronics). Another function of the right MID is housing and supporting the coils, and protecting them from the system vibrations.

4.2. Phase 0: Preliminary Phase

Phase 0 consists in a preliminary functional analysis of an existing product. To obtain this analysis, the main functional subsystems are added to the EF-M of the product and translated into a DSM, to visualize interfaces and interactions among them. The information about the product functionalities are obtained by conducting interviews with the company specialized workers and searching the product technical documentations. The first breakdown of the product will be simple and generic, but will also highlight the main logical links among components and serve as a base for future modifications.

It is suggested to break down the product in about twenty subsystems, to understand their uncompromisable functions. The first DSM will directly derive from the EF-M model and here the interactions among subsystems will be mapped in Spatial (S), Energy (E), Information (I), Material (M) or any combination of the four (SE, IM, SEM...). For this preliminary phase, the breakdown must be kept concise and general, since it is not required a comprehensive knowledge of the product: this will be built during the next



Legend:

1. **Fixed part:** structural enclosure of the breaker.
2. **Mechanical interface:** display, buttons, levers...
3. **Contacts system:** assemblies which allow current transfer and interruptions.
4. **Arc chamber:** element which extinguish the plasma arc caused by the opening of the contacts.
5. **Trip-unit:** it rules circuit opening and closing operations.
6. **Stored energy mechanism:** springs that link the action of the coils and operating mechanism, motor group.
7. **Operating mechanism:** connection between springs and moving contacts.
8. **Accessory module:** it consists of the coils, that activate the circuit's operations, and the right plate for accessories, that supports and protect them and transmit their signals to the trip unit.

Figure 4.2: Exploded view of the main ACBs subsystems, with a focus on the right plate for accessories (adapted from ABB's technical catalogs [95]).

phases.

Figure 4.3 shows the EF-M and the DSM of an ACB, with a focus on the accessory module (reference to Figure 5.2 and Figure 5.3 for the complete models). The functional blocks of the EF-M represent the main subsystems of the breaker (such as fixed part, arc chamber...) and the dotted lines point at the interactions among them. The model is sided by a DSM that explains these interactions. As shown in the figure, the function of the whole accessory module is remotely opening and closing the circuit. When the block is broken down into its main components, the functions are detailed as well. In fact, the module is composed by distinct coils, that operate under different faults conditions, and by their structural enclosure, the right plate for accessories. The operations of the coils are ruled by the trip unit, that sends information through the right plate for accessories. For this reason, coils and the right plate for accessories present spatial-information ("SI") type of interaction in the DSM, while the trip unit eco-system only exchange information with coils and plate ("I"). In the case of a circuit breaker, no material (M) interaction have been mapped, because plasma generation is considered energy (E) exchange.

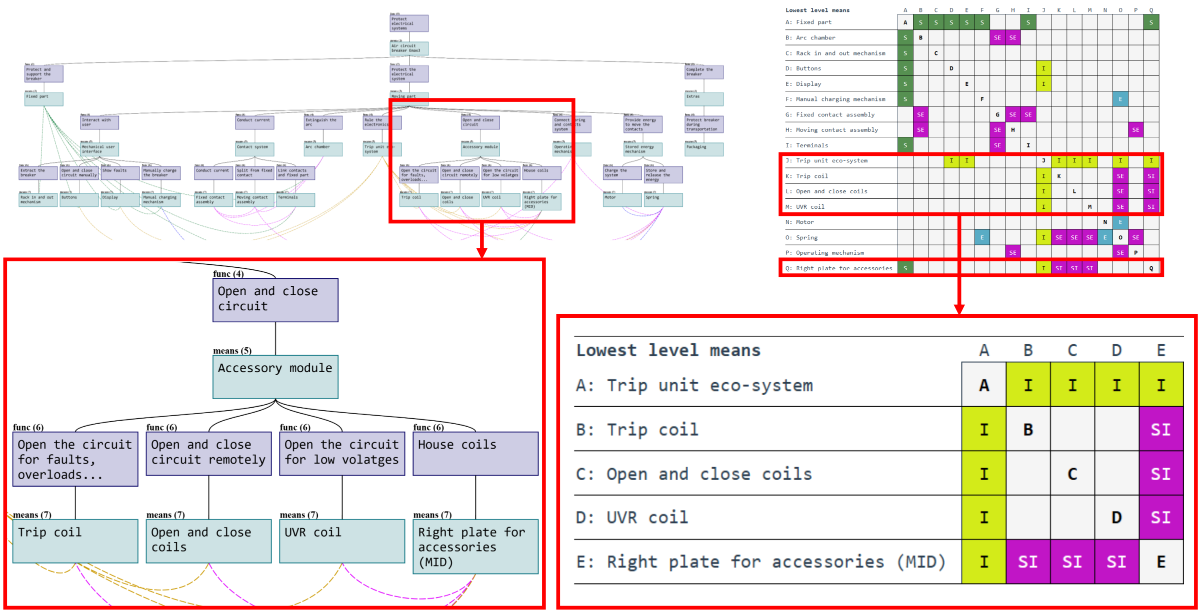


Figure 4.3: EF-M tree model and DSM of an ACB, with a focus on the accessory module, obtained using Trinity-Systems Modeling [44].

4.3. Phase 1: Requirements Identification

Phase 1 of the methodology involves identifying customers' NFRs, with a focus on the requirements that are sustainability-oriented. FRs have been identified during Phase 0 (Section 4.2) and are not considered for the current requirements identification, because they are the reason why customers purchase the products, therefore, they have the highest priority. In contrast, NFRs are often negotiable, hence it is important to define a scale to evaluate their relevance among customers. For example, it is possible that some customers are willing to compromise the dimensions of a product to reduce the costs, or maybe to increase the dimensions to enhance performance.

The literature research underlined the necessity to consider NFRs deriving from both LCA-based analyses and circular strategies. For what concerns LCA-based analyses, the most representative NFRs are "Material sustainability" and "Energy efficiency". Some aspects of "Energy efficiency" can be considered FRs, but the present work does not consider technologies directly aiming at making the product more efficient in terms of performance, but in terms of sustainability. For example, in the case of an ACB, the energy efficiency is usually considered from two perspectives:

1. How to reduce generated power losses;
2. The strategies to avoid that the power losses increase the breaker's temperature above the standard limitations.

Since this work considers "Energy efficiency" from the sustainability point of view, the solutions proposed will only address the first perspective, because the realization of an improved cooling system would not affect the product environmental impact.

The circular potential of a product is conveyed by the NFR "Maximize product lifetime and value utilization within the economy" [71]. This requirement is not immediate to understand, because there is not any standardized framework to measure products circularity potential [72] and it requires extensive knowledge on the product use phase. However, it refers to the components or subsystems where the 10Rs circularity strategies could be applied with highest environmental benefits. For example, increasing the repairability of a component that is frequently substituted allows to spare the impact of the spare part production, but it is difficult to foresee what components will fail the most in a new product. The present thesis considers the 10Rs framework a solution to the circular potential requirement, as they are not directly needed by the customers, but are strategies that help obtain the lifetime extension and maximum resource utilization NFRs.

These methodology-specific permanent requirements are integrated into some case study industry-specific NFRs, to be researched through a market analysis. The analysis involves benchmark analysis of competitors' product solutions and interviews with company's service and sales experts. The result of these operations leads to the identification of NFRs of:

- Internal stakeholders, that are involved in the production company;
- External stakeholders, that are the customers and outside parties affected by the company;
- Sustainability-oriented NFRs.

However, before researching the NFRs, a concise characterization of the customers that interact with the company should be performed. This characterization allows to position the company on the market (B2B, B2C...) and to define its usual customers (company size, budget, geographic are, innovation degree...). Once the characterization of customers is complete, the focus of the quest moves to the NFRs identification, and more interviews and literature research are conducted. Here, the attention is on the product, the requirements that it should satisfy and how competitors are approaching the NFRs.

Another important aspect to define is the time span the interviews are referring to. In fact, since platform design allows the agile integration of present and future changes, the company, customers and NFRs expected evolution should be analyzed in a time span of around fifteen years, depending on the sector characteristics.

The combined research for information will offer a complete landscape of NFRs, that will be to reorganized and listed for each range of customers. To perform this operation, Kano models are used to collect qualitative workers insights [96] and binary pairwise comparison [97, 98] is implemented to manually prioritize requirements [99] and to translate the information collected into quantitative. In the future it would be useful to automate the process, starting from the extraction of the requirements [100, 101] to the DSMs evaluation. The result of the market analysis is a priority matrix, that serves as a base for deriving the market segmentation of the product's customers.

Figure 4.4 shows the priority matrix for ABB's Emax ACB series. The customers for this product series vary from very big innovative businesses as data centers (high-end range) to small traditional industrial plants (low-end range). The expectations of both ranges are considered first in the present year (2026) and after 14 years (2040). Before turning them into requirements, the needs collected from interviews are translated into requirements and sorted in terms of relevance to each kind of customer. The methods used during

Priority Matrix		High-end customers 2026	High-end customers 2040	Low-end customers 2026	Low-end customers 2040
FRs	**Basic needs**	must-have	must-have	must-have	must-have
Internal Stakeholders NFRs	Cost-effectiveness	13%	9%	16%	15%
	Ensure carry-over	5%	2%	11%	5%
	Standard and regulations adherence	18%	18%	18%	18%
External Stakeholders NFRs	Connection to supersystem	0%	11%	0%	7%
	Dimensions reduction	4%	0%	7%	2%
External + Sustainability	Zero downtime	16%	15%	13%	13%
	Energy efficiency	11%	16%	15%	16%
Sustainability-Oriented NFRs	Ability to provide sustainability insights to supersystems	15%	4%	5%	0%
	Material sustainability	9%	7%	9%	9%
	Maximize product lifetime and value utilization within the economy	7%	13%	4%	11%
	Social sustainability	2%	5%	2%	4%
		100%	100%	100%	100%

Figure 4.4: Priority matrix for ABB's Emax ACBs series. The figure shows the relevance of each NFR to different customers' ranges.

this phase are Kano models and binary pairwise comparison matrices, that explain the granularity of the relevance percentages shown in the priority matrix. Other than being classified in terms of relevance, the NFR are grouped based on the type of stakeholder that requires them, from the aforementioned list: internal, external, sustainability-related. The single NFRs are analyzed and explained in Section 5.2.2.

The priority matrix shows the relevance of each requirement for every range of customers, and due to the different in the scores, it will probably result in a different optimal product architecture for each category. However, one of the advantages of platforming is the possibility to analyze how much the optimal architectures would differ one from another and determine the optimal number of variants.

4.4. Phase 2: Component-Sustainability Mapping

Phase 2 maps the relation between the satisfaction of one sustainability-oriented NFR and the product subsystems, throughout the lifecycle. This means highlighting the components with the highest environmental impact or with the highest margin for sustainable redesign, namely how much the environmental footprint could be reduced through the implementation of a new design solution. The essential tools to perform this mapping operation are product LCA analyses and/or EPDs.

These computation are analyzed to obtain the emissions linked to the manufacturing phase of the product and the rules to dispose it. Moreover, 10Rs circularity strategies are used to compensate LCA-based analyses for use phase and end-of-life predictions.

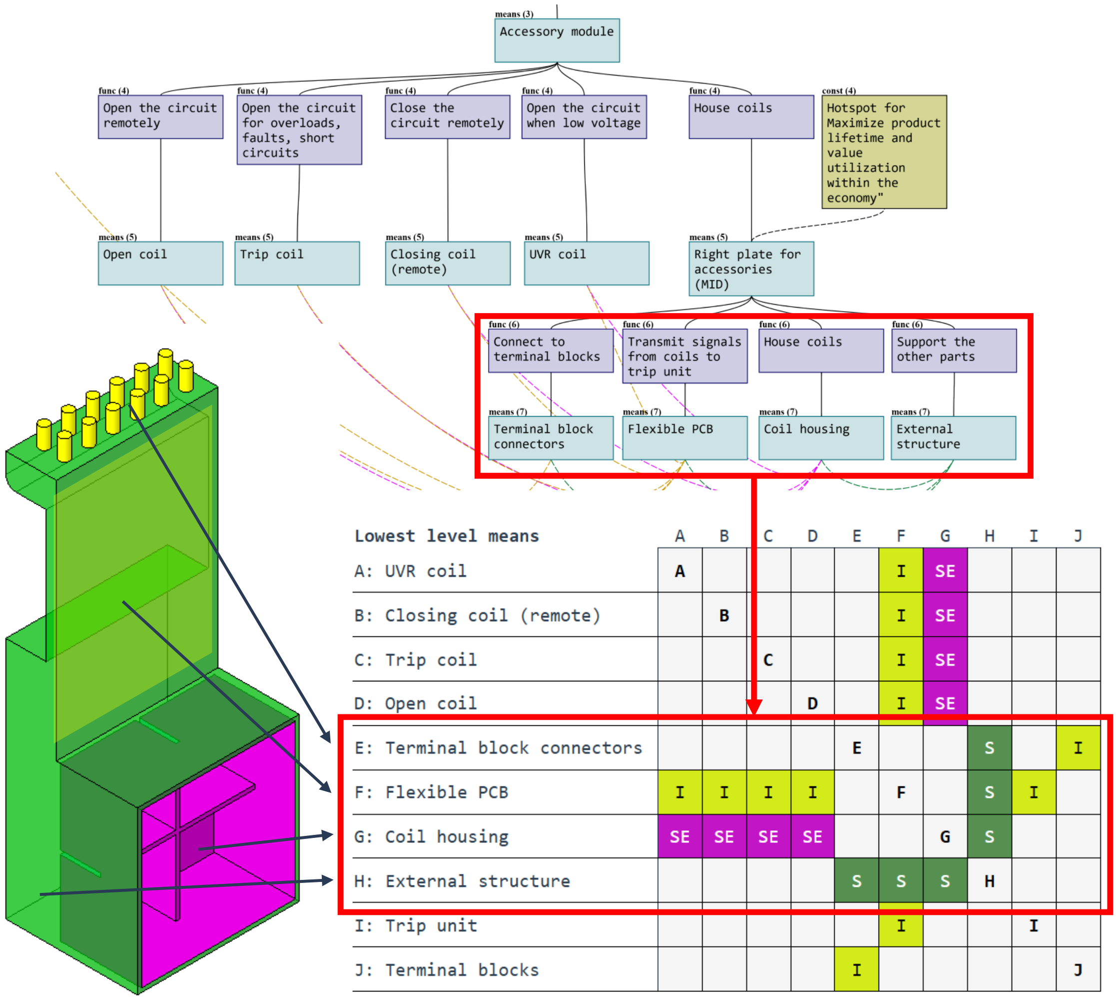
To identify the systems that are hotspots for sustainability, a quantitative unit of measurement is assigned to every NFR. Among the alternatives present in the literature (kilograms of waste created, Rs strategies-based scoring system [72]), the units of measurement used in the present methodology are:

- Kilograms of CO_2 equivalent emissions for "Material sustainability";
- Watts associated to power losses for "Energy efficiency";
- Number of spare parts substitutions and components lifetime for "Maximize product lifetime and value utilization within the economy".

At this point, the systems that are responsible for most of the emissions computed by the LCA and the systems where one of the Rs circular strategies can be applied, are manually listed, added to the product EF-M and are "flagged" with different elements of the model. The model in this phase presents a more detailed breakdown of the sustainability hotspots, that are marked with the NFR they are responsible for. This detailed breakdown will help in the phase of alternative DS generation, because many product components are integrated solutions with more than one function: the new DSs could be additions to the architecture, could directly replace the current components, but could also modify just a part of it, without replacing it entirely. For what concerns the EF-M model, the more accurate and detailed is the functional breakdown, the easier it gets to find new solutions, that address just one problem each [102].

The detailed functional breakdown of an Emax ACB right MID is shown in Figure 4.5. The right plate for accessories is an hotspot for "Maximize product lifetime and value utilization within the economy", because it is one of the spare parts that is more often substituted. This is due to the vibrations that this component must resist to during both breakers' operations and maintenance activities. As a matter of fact, the right MID is especially solicited when coils are extracted and put back into place during maintenance operations.

As shown in the figure, the functions performed by the plate are various and it is important to analyze them in order to effectively modify the component. Among these, the external structure serves as support for coils, the coil housing is the interface among plate and coils, while the internal flexible PCB and terminal block connectors transmit signals from



Lowest level means	A	B	C	D	E	F	G	H	I	J
A: UVR coil	A					I	SE			
B: Closing coil (remote)		B				I	SE			
C: Trip coil			C			I	SE			
D: Open coil				D		I	SE			
E: Terminal block connectors					E			S		I
F: Flexible PCB	I	I	I	I		F		S	I	
G: Coil housing	SE	SE	SE	SE			G	S		
H: External structure					S	S	S	H		
I: Trip unit						I			I	
J: Terminal blocks					I					J

Figure 4.5: Focus on the right plate for accessories for EF-M model and DSM, as it is a hotspot for "Maximize product lifetime and value utilization within the economy".

and to the trip unit.

4.5. Phase 3: Sustainable Solutions Generation

Phase 3 focuses on the generation of DSs that satisfy the sustainability-oriented NFRs. The new solutions are generated and added to the EF-M of the product as alternatives to the current architecture. Each alternative solution generates a different set of DSMs, in order to represent every combination among them. The integration of the sustainable DSs into the product DSM allows to study the new dependencies among different modules and to modify the interfaces accordingly. Since the tool used to implement the present methodology only allows four letters to characterize DSM interactions (S, E, I, M) and the EF-M model of the product didn't present material exchanges, the interfaces modified by the addition of the new DSs are marked with the letter "M".

Figure 4.6 shows portion of ACB's EF-M where some solutions for "Maximize product lifetime and value utilization within the economy" NFR are listed. In particular, the figure focuses on how to increase the right MID repairability, by having it to absorb vibrations. The new DSs that satisfy the other sustainability-oriented NFRs are shown in the Section 5.2.4. The solutions to extend the right plate for accessories lifespan generate four different DSMs, but, if they are combined with the DSMs resulting from the other sustainable solutions addition, the number reaches 576 different matrices.

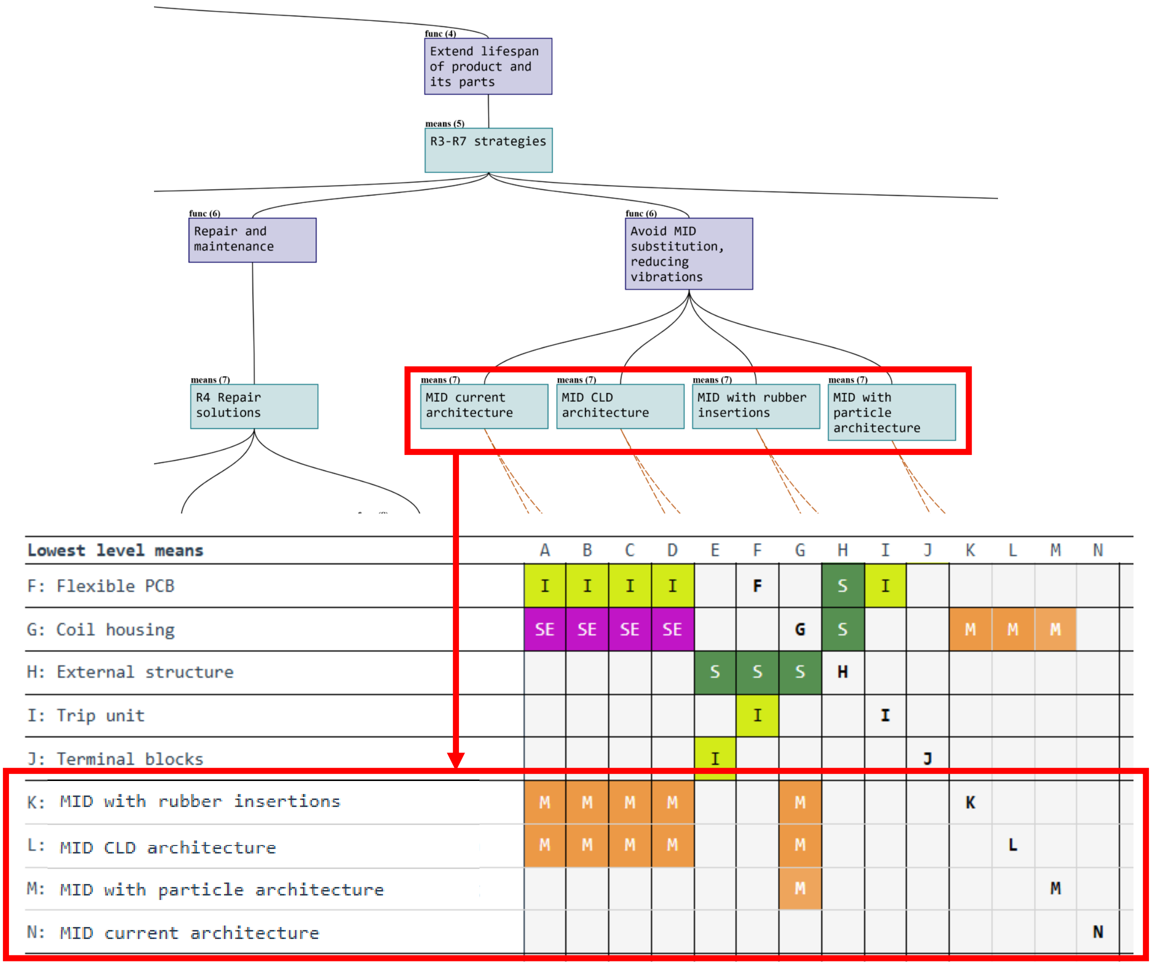


Figure 4.6: Sustainable DSs to increase plate for accessories repairability (R4), integrated into the DSM of the product.

The solutions regarding the ACB's right MID architecture are:

1. The addition of some rubber inserts;
2. The addition of a viscoelastic layer to absorb vibrations (CLD, Constrained Layer Damping method);
3. The redesign of the component to add a particle damping architecture;
4. The current undamped architecture.

After the definition of the new solutions, their integration into the product architecture is studied and the eventual modifications to the other modules interfaces marked with an M (as shown in Figure 4.6). Being in a preliminary concept definition phase, the integration of new design solutions is not studied in detail. However, the "M" in the DSM highlight how, among these solutions, the adoption of the current architecture would not modify any interface, while the particle architecture would modify the interface between MID structure and the coils, because coil housing would need a complete redesign. Finally, rubber or a viscoelastic layer insertion the interactions with the coils, because they would absorb vibrations from them without transmitting solicitations to the MID structure.

4.6. Phase 4: Alternative Solutions Evaluation

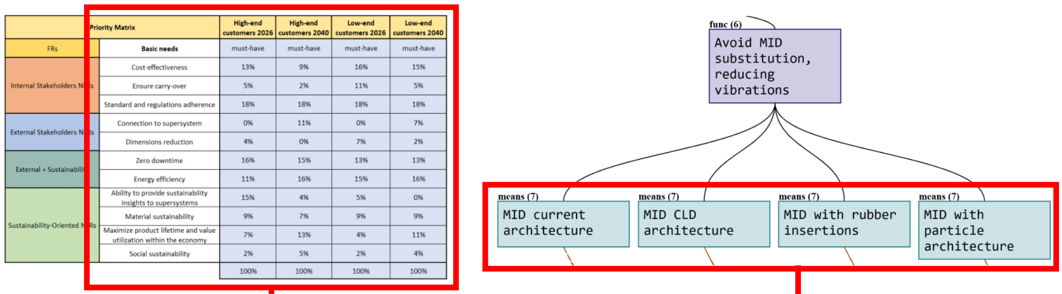
Phase 4 aims at evaluating the alternative solutions added to the EF-M model in Phase 3 and ranking the generated DSMs accordingly. To obtain this ranking, the DSs are graded based on their correlation with the NFRs identified in Section 4.3. The evaluation scores associated with the alternative DSs are summed within the DSM they belong to and the DSMs are ranked from the one that has the highest grade to the lowest, for every range of customers. After thinking about the new solutions integration, some ulterior differences about customers may raise. In that case, the customers' segmentation can be modified and adapted to the information collected.

To perform the evaluation, the DSs are inserted in the evaluation grid shown in Figure 4.7. Here, one of the five allowed degrees of correlation, $-9, -3, 0, +3, +9$, is associated with the satisfaction degree that each DS provides to a stakeholder NFR. $+3$ and $+9$ scores indicate moderate and strong positive correlation, while -3 and -9 point at negative correlations. 0s indicate that the DSs do not affect the satisfaction of the specific NFR. When these scores are summed for each DS contained in each DSM with an external Python code, the DSMs are ranked in terms product architecture suitability. This semi-quantitative evaluation is inspired by the scoring system widely employed in MFD [40].

Figure 4.7 shows the evaluation of the solutions that increase the right MID lifespan.

The stakeholders NFRs are presented in the first column of the grid. The following four columns are used to show the relevance assigned to each NFR by every range of customers, while the last four columns present the relations scores between DSs and NFRs satisfaction.

For what concerns this component, the current architecture is the most cost-effective and compliant with standard and regulations. However, the sustainable solutions extend its lifetime and benefit the breaker's availability. The disadvantages characterizing each new DS are the standard adherence for the rubber addition, since it degrades at high temperatures and needs frequent substitution [103]. On the other hand, particle damping would entail a complete redesign of the component, not ensuring carryover of the part and will increase the dimensions of the MID [104]. Finally, adding a viscoelastic layer would add new materials to the product, damaging material sustainability, but also overcome the problems presented by the other alternatives [105].



Alternative solutions evaluation	High-end customers 2026	High-end customers 2040	Low-end customers 2026	Low-end customers 2040	MID current architecture	MID damped architecture: rubber insertion	MID damped architecture: particle damping	MID damped architecture: CLD
					1	2	3	4
Cost-effectiveness	13%	9%	16%	15%	0	-3	-3	-9
Ensure carryover	5%	2%	11%	5%	0	0	0	0
Standard and regulations adherence	18%	18%	18%	18%	0	0	-9	0
Connection to supersystem	0%	11%	0%	7%	0	0	0	0
Dimension reduction	4%	0%	7%	2%	0	-3	-3	-9
Zero Downtime	16%	15%	13%	13%	0	3	3	3
Energy efficiency	11%	16%	15%	16%	0	0	0	0
Ability to provide sustainability insights to supersystems	15%	4%	5%	0%	0	0	0	0
Material sustainability	9%	7%	9%	9%	0	-3	-9	-3
Maximize product lifetime and value utilization within the economy	7%	13%	4%	11%	-3	3	3	9
Social sustainability	2%	5%	2%	4%	0	0	0	0

Figure 4.7: Plate for accessories alternative solutions rating against customers' NFRs.

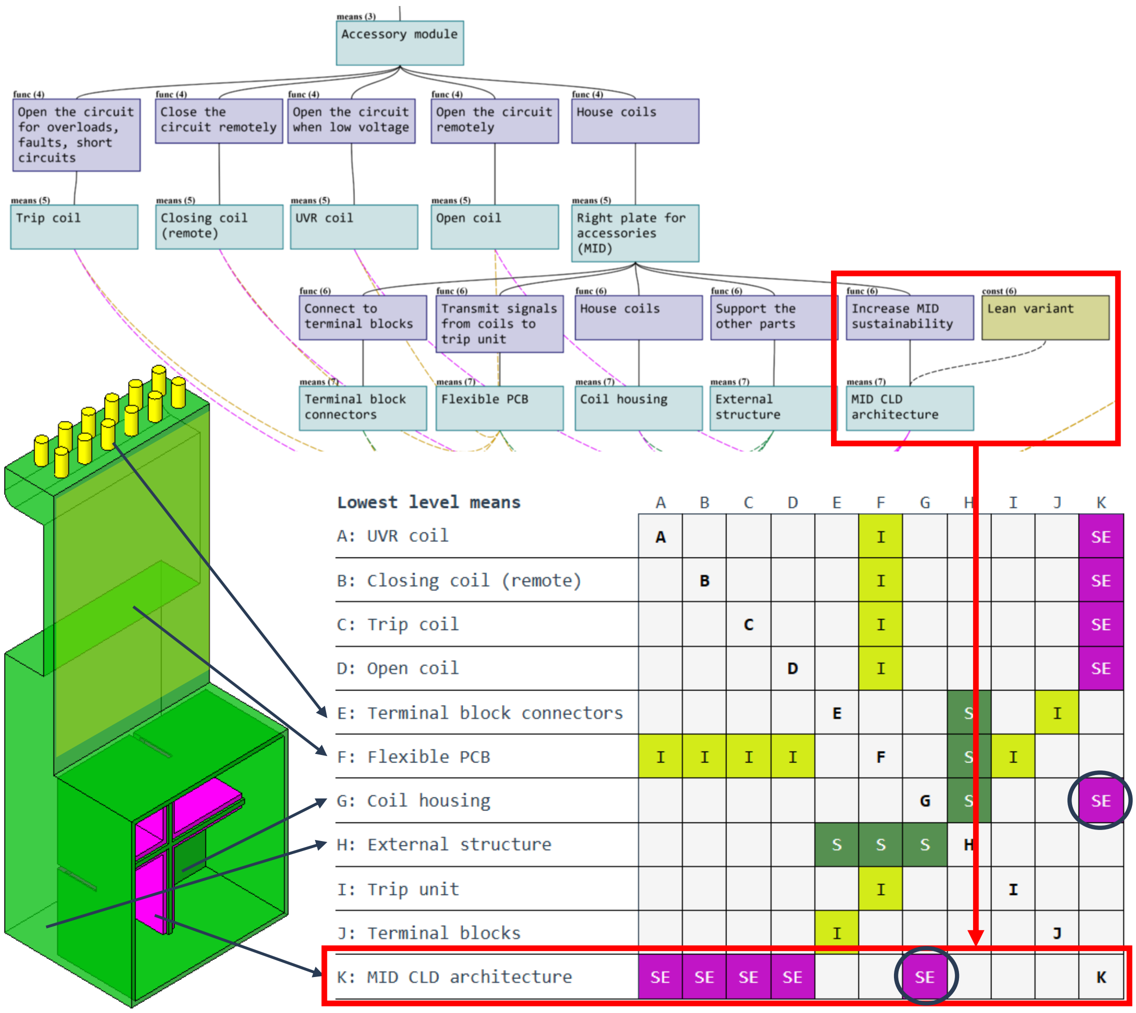
Once completed the grid, the evaluation starts. The insertion of rubber in the coils housing section of the right plate for accessories adds a moderate cost, for this reason the correlation score is -3. Now, -3 is multiplied by the relevance of cost-effectiveness for high-end customers of 2026. That gives a partial score of -0.39 to this DS. By completing the scalar product between the column of rubber insertion DS and the relevance of requirements for high-end customers of 2026, the score -0.57 is obtained. This means that every DSM presenting the DS "MID damped architecture: rubber insertion" will have a score of -0.57 for the alternatives evaluation of the MID architecture. This score will be summed to those of the other Design Solutions of the DSM, and the DSM with the highest score will represent the most suitable product architecture for high-end customers of 2026. The same operations will be performed for the other types of customers.

After running the external code computing the DSMs classification, the high-est ranked DSM for low-end customers of 2026 is DSM 468, that presents the current MID architecture (Figure 4.5). This is because low-end customers prioritize cost-effectiveness above any other NFR and have a low interest in sustainability. In contrast, high-end customer already value sustainability, this is why their highest ranked matrix is DSM 461, and presents an additional damping layer (CLD) between coil housing and coils (Figure 4.8). This solution benefits the NFR "Maximize product lifetime and value utilization within the economy", by protecting the right plate for accessories from cricks and damages.

4.7. Phase 5: Product Architecture Analysis

Phase 5 focuses on analyzing the highest-ranked DSMs resulting from Phase 4 and integrating their DSs in the product architecture. To obtain a new architecture, new interfaces and interactions are studied in order to make them compatible. The solutions that are common for every range of customers will constitute the platform core, while the different alternatives will represent the platform extension. The sustainable solutions will be marked with the platform variant they belong to, through the use of constraints slots. Once defined the new product architecture, the evaluation matrix is analyzed again, to find areas of further improvement. During this stage, it could be useful to repeat the platform development process centered around the NFRs that are not satisfied by the implementation of new solutions.

Three of the highest-ranked DSMs out of the four current ranges of customers present the addition of a viscoelastic layer in the architecture of the right plate for accessories. Figure 4.8 shows the changes that the implementation of this solution would cause to the plate-coils interfaces. The interaction between the MID and the coils would stop being energetic, due to the absorption of the vibrations performed by the new layer. Therefore, the SE (spatial-energetic) interaction will move between coils and damping layer and between damping layer and housing. This addition will contribute to extend the MID lifetime and spare the impact of manufacturing a substitute. This configuration is characteristic of the "Lean" platform variant and it is the only one considered for this example. However, more variants can result from the methodology application, and they will be distinguished by "Incompatible" interactions among alternative solutions belonging to different platform extents.



Lowest level means	A	B	C	D	E	F	G	H	I	J	K
A: UVR coil	A					I					SE
B: Closing coil (remote)		B				I					SE
C: Trip coil			C			I					SE
D: Open coil				D		I					SE
E: Terminal block connectors					E			S		I	
F: Flexible PCB	I	I	I	I		F		S	I		
G: Coil housing							G	S			SE
H: External structure					S	S	S	H			
I: Trip unit						I			I		
J: Terminal blocks					I					J	
K: MID CLD architecture	SE	SE	SE	SE			SE				K

Figure 4.8: Addition of a damping layer to the right plate for accessories and relative modifications to plate-coils interface.

Although its tangible impact on the component sustainability, this solution would have not be found through a LCA-based approach alone. This example remarks the relevance of the circular strategies employment in the sustainable redesign process. Nonetheless, the addition of a new layer damages NFRs like "Cost-effectiveness" and "Ensure carryover".

It would be useful to go back to Phase 1 and repeat the analysis focusing on satisfying these NFRs.

5 | Methodology application: a case study on ABB's Emax3 series of Air Circuit Breakers

This chapter will show the application of the methodology for the development of a sustainability-oriented platform to the industrial case of an Air Circuit Breaker (ACB). In particular, the present methodology will focus on the reorganization of the breaker's mechanical systems, to increase their sustainability. All the steps presented previously will be applied to the ACB sustainable redesign.

5.1. Goal and scope

The case study for the sustainability-oriented platform design methodology is ABB's family of Air Circuit Breakers (ACB) Emax3. Emax3 is designed to be installed on the circuits of critical power distribution systems such as data centers, utilities, industrial plants and infrastructure applications. This family of breakers offers advanced protection, high-reliability, operational continuity and intelligent energy management [93].

Emax3 series is available in more sizes and starts from a compact frame (Figure 5.1), with an IEC Icu (International Electrotechnical Commission Ultimate Short-Circuit Breaking Capacity) of 50 kA at 690 V, up to the most high-performance model, with an IEC Icu of 120 kA at 690 V [93].

In terms of sustainability, the breakers of Emax3 family are provided with an assessment involving their entire lifecycle, part of ABB's EcoSolutions program. Other than the LCA from cradle-to-grave, Emax3 is certified with the EPD, in order to increase the transparency across the company's value chain. The company ABB also follows some circular economy principles, such as the implementation of monitoring and predictive maintenance techniques, and recyclability increasing of the components parts, obtained through Design For Disassembly (DFD) methodologies.

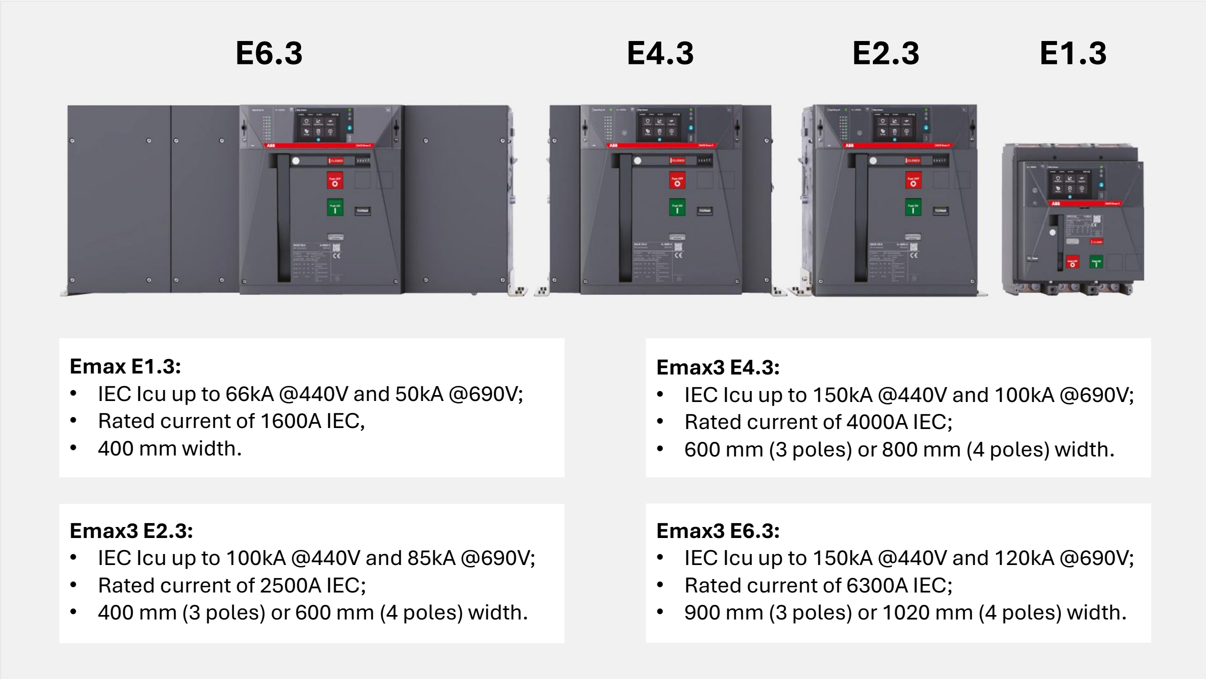


Figure 5.1: Technical characteristics of the Emax3 platform, sorted by model. Adapted from ABB's technical catalogs [5].

The goal and scope of the present methodology application is the sustainability-oriented platform redesign of ABB's Emax3. This product is optimized in terms of innovation and performance, and some sustainability solutions have already been implemented. However, new Design Solutions will be proposed and evaluated based on a sustainability-oriented platform design approach to show the validity of the methodology and analyze the trade-off among sustainability and the other requirements. The analysis is limited to the breaker's mechanical architecture, the electronics will not be taken into consideration.

5.2. Methodology application

The next sections will present the steps of the methodology illustrated in Chapter 3, applied to ABB's Emax3 ACB series.

Emax3 family of circuit breakers presents four different models (Figure 5.1), with various weights and dimensions. This work will refer to the quantitative data of Emax3 E1.3, unless specified differently. However, every information can be scaled to adapt to the other formats.

5.2.1. Phase 0: Preliminary Phase

In the preliminary phase of the methodology application, the ACB Emax3 has been broken down to its main functional blocks (Figure 5.2). The partition at this point is simple and generic, it is not necessary to acquire a detailed knowledge about the product yet, but it will be reviewed and modified throughout the other phases of the application. The main functional blocks of Emax3 ACB series are (Figure 4.2):

- **Fixed part**: a structural enclosure which supports the breaker and protects it from external agents.
- **Mechanical interface**, that contains all the elements through which the user interacts with a breaker: display, buttons, manual charging lever and draw-out mechanism.
- **Contacts system**: the assemblies which allow current transfer and interruption, namely the breaker's main conductive path.
- **Arc chamber**, that is the element which extinguish the plasma arc caused by the opening of the contacts.
- **Trip-unit eco-system**: the "brain" of the breakers, the system which rules every opening and closing operation.
- **Accessory module**: it contains all the coils that physically activate the circuit's opening or closing operation.
- **Stored energy mechanism**, the springs that link the action of the coils and operating mechanism, and the motor group which charges them.
- **Operating mechanism**: it connects the action of the springs with the moving contact, physically rotating and splitting the contacts.
- **Extras**, that are the elements that are not part of the product architecture, but are still necessary to commercialize it, such as packaging and instructions.

In the DSM in Figure 5.3, the interactions among subsystems are mapped in Spatial (S), Material (M), Information (I), Energy (E) or a combination of the four. In this case, the fixed part of the circuit breaker interacts spatially with many of the other elements, due to its structural and protective functions. The main energy exchanges regards the contact systems, while the information are usually transmitted to the trip-unit, as it constitutes the ruler of the electronics.

To perform the functional breakdown of Emax3, technical documentations have been stud-

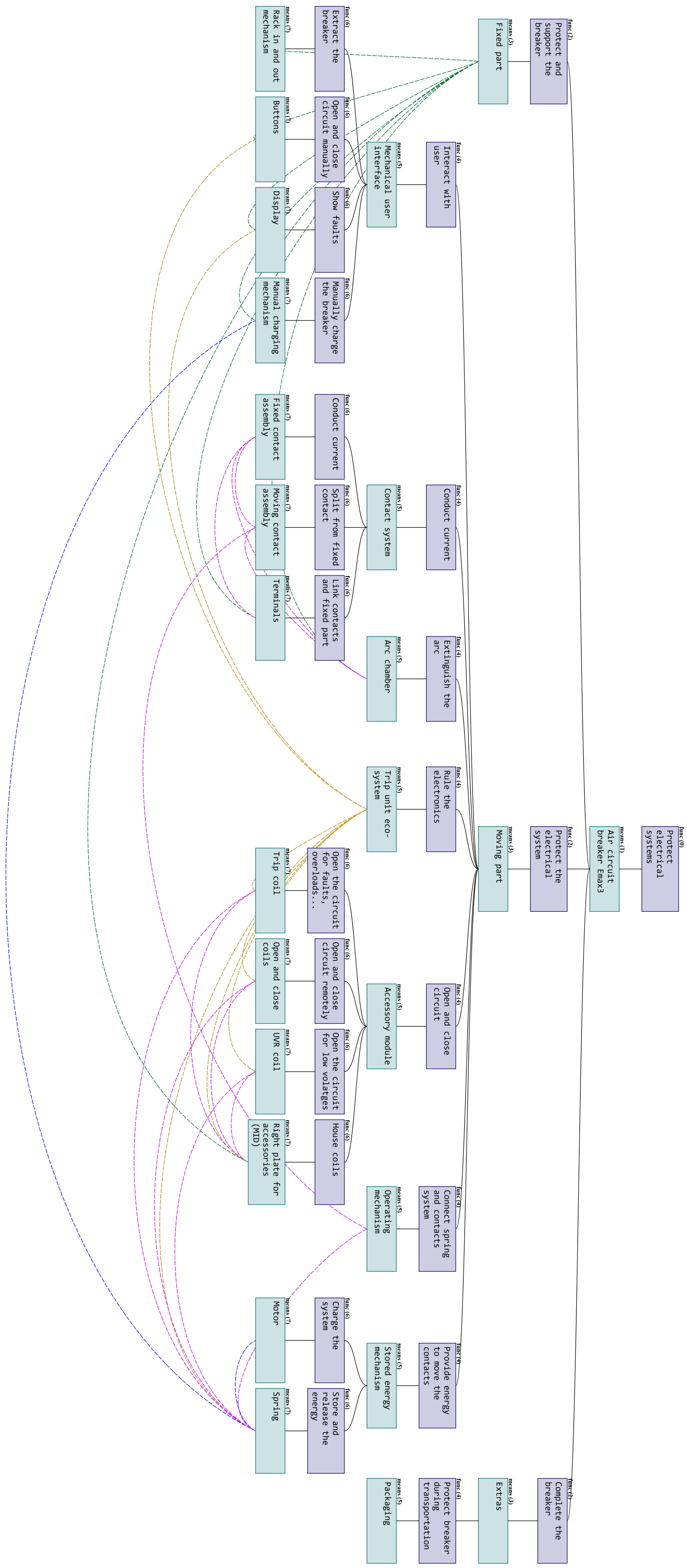


Figure 5.2: Functions-Means model of Emax3, broken down to its main subsystems.

Lowest level means	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
A: Fixed part	A	S	S	S	S	S			S					S				S
B: Arc chamber	S	B					SE	SE										
C: Rack in and out mechanism	S		C															
D: Buttons	S			D						I								
E: Display	S				E					I								
F: Manual charging mechanism	S					F												
G: Fixed contact assembly		SE					G	SE	SE									
H: Moving contact assembly		SE					SE	H								SE		
I: Terminals	S						SE		I									
J: Trip unit eco-system				I	I					J	I	I	I		I			I
K: Trip coil										I	K				SE			SI
L: Open and close coils										I		L			SE			SI
M: UVR coil										I			M		SE			SI
N: Motor	S													N	E			
O: Spring										I	SE	SE	SE	E	O	SE		
P: Operating mechanism								SE							SE	P		
Q: Packaging																	Q	
R: Right plate for accessories (MID)	S									I	SI	SI	SI					R

Figure 5.3: Design Structure Matrix of Emax3, broken down to its main subsystems.

ied and interviews with company's representatives have been conducted. This research work also resulted in the identification of the breaker's FRs, that are:

- Detection and interruption of ground faults;
- Current interruption at its rated capacity;
- Circuits protection by interrupting sustained overcurrent caused by overloads;
- High fault current interruption during short-circuits events;
- Critical currents avoidance.

5.2.2. Phase 1: Requirements Identification

The objective of this phase is the identification of Emax3 NFRs. The focus of the research are NFRs linked to sustainability, but also to performance, regulations, costs and all the categories that could interest breakers' customers and producers. To obtain it, different interviews with sales and service company representatives have been conducted and a benchmark analysis of customers' needs and competitors' offers has been performed.

For what concerns the interviews, the ABB workers involved had experience across products sustainability, customers' service, mechanical design, materials and sales. The questions were centered around the characterization of ABB's customers and what they could expect from Emax3 breakers series. The benchmark analysis, on the other hand, collected various sustainability reports to frame how the subject is addressed by ABB and its major customers and competitors [22–29]. The sustainability reports of customers and competitors focus on:

1. Decarbonization and energy efficiency;
2. Circularity and resources efficiency;
3. Regulations and social sustainability.

From the integration of interviews and research activities, a characterization of ABB's customers was developed, with a focus on their level of interest in sustainability-related aspects (Figure 5.4). The analysis also provided an overview of the main NFRs associated with the Emax3 circuit breakers series.

This research work highlighted some sustainability keypoints. For instance, companies' sustainability strategies mainly focus at the products' beginning-of-life (materials extraction and manufacturing) and at the end-of-life (how to reuse, remanufacture or recycle the components). However, the most polluting phase for ABB's products is the use phase, due to the extended lifespan of their products. The use phase is also the stage where customers are more involved, and this will increase the relevance of predictive and simplified maintenance strategies.

Modularity is often mentioned among sustainability NFRs, but it is in fact a solution to satisfy other NFRs, such as easing the disassembling (and so the end-of-life treatments) and fostering predictive maintenance and repairability. Sometimes, circularity is considered a NFR as well, but the present work will consider it as an ensemble of strategies to satisfy other sustainability NFRs.

Geographically, the interest for sustainability is concentrated in Europe, but it is gradually spreading in China and Australia. At the moment, social sustainability has a relative low relevance for customers and it strongly depends on the regulations of the country of manufacture. In the future, we can assume that the relevance of sustainability will increase in the rest of the world, starting from attention to the environment and gradually involving social sustainability.

The discrepancies in the interest for sustainability, allowed us to define two kind of customers: an high-end range of customers, indicating a strong interest in sustainability and the means to implement sustainable strategies, composed by big companies in innovative

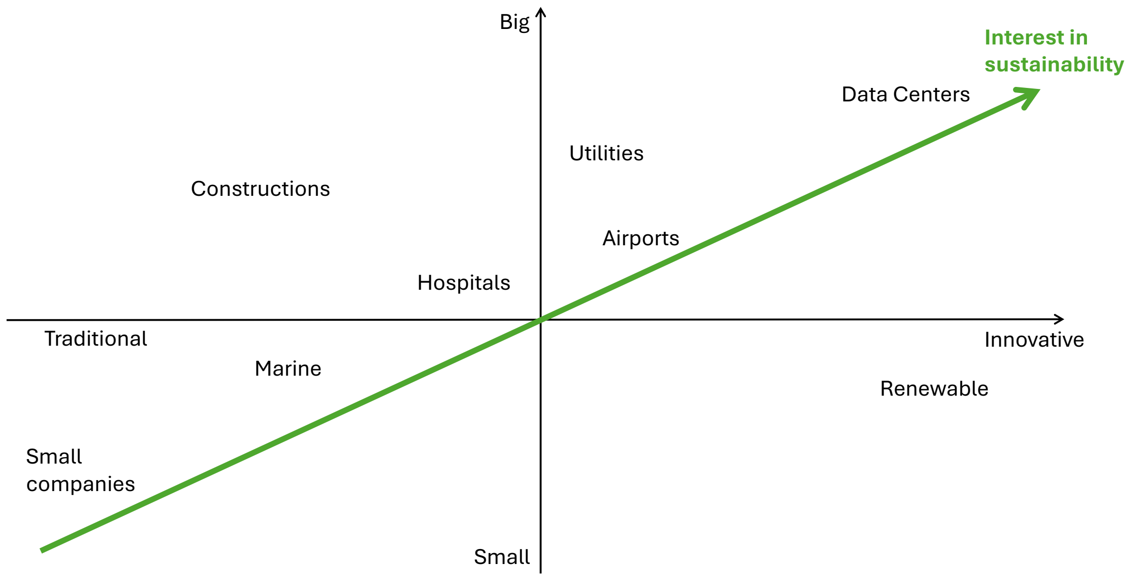


Figure 5.4: ABB's customers characterization in terms of size, innovation degree and interest in sustainability.

sectors (data centers, utilities, renewable...), and a low-end range of customers, made by the small companies in traditional sectors, with a little interest in sustainability. The present expectations of these two types of customers and an estimation of how they would change in a time span of around fifteen years have been analyzed, for a total of four ranges of customers:

- High-end customers of 2026;
- High-end customers of 2040;
- Low-end customers of 2026;
- Low-end customers of 2040.

As shown in Figure 5.5, the information resulting from interviews and benchmark research were collected into Kano models for each kind of customers.

It resulted that the high-end segment of the (2026) market, constituted by big businesses as utilities (Enel, Enedis. . .) and data centers is driven by an image enhancement desire and have more means to implement sustainable measures. Their sectors are very energy-consuming, therefore they are really interested in improving the breakers' energy efficiency, but their main focus is the possibility to have the maximum uptime possible and the sustainability of their materials (recycled, low-carbon, bio-based. . .). Moreover,

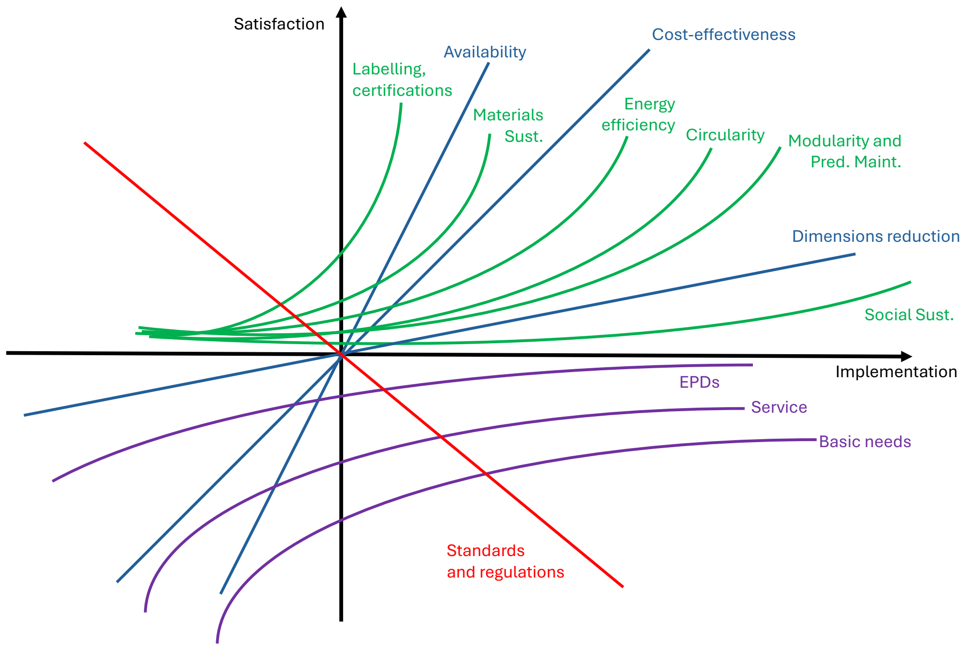


Figure 5.5: Kano model for high-end customers in 2026.

they often require customized services as take-back and ad hoc "What if" scenarios certifications provided with the purchase.

By 2040, we can assume that environmental sustainability will become more of a constraint and less of a delighter to customers' eyes and social sustainability will contribute to enhance the company's image. The focus on energy will translate into an interest in finding new energy sources (nuclear, hydrogen...) and integrating the switchgears into more complex systems, this will demand an intelligent energy management. The most disruptive prevision for the future is undoubtedly the shift of the products offered by ABB: not physical anymore, but under the form of a subscription, with the focus moving from the physical switchgears to the circuits protection. This turning point will contribute to enhance products sustainability, since less of them will be necessary to serve the same number of companies.

For what concerns the low-end segment, composed of small companies in 2026: these companies are focused on the economic driver and not really interested in sustainability. These two aspects can however be combined enhancing the energy efficiency of the product, because it permits long-term savings. Also, they don't value the implementation of a take-back service, as they already recover precious metals from their old breakers and keep the rest of the components to have spare parts always available. This aspect associates them with Asian and American firms, who also disassemble old breakers because of the cheaper labor cost and the higher cost of spare parts.

In 2040, low-end segments will probably shift their focus from economics to sustainability, environmental and social, probably because of new regulations, fines for the produced emissions and higher difficulties in finding critical materials.

To translate the qualitative information collected during interviews into quantitative, binary pairwise comparison matrices have been used for each range of customers (Figure 5.6. Here is the list of the identified NFRs.

For internal stakeholders:

- Cost-effectiveness: the breaker must be affordable to produce and sell at a competitive price.
- Ensure carry-over, because the implementation of new technologies must be studied and is time and resources-consuming.
- Standard and regulations adherence, this is an uncompromisable requirement to commercialize breakers.

For external stakeholders:

- Connection to supersystem: the energy sector is evolving towards multi-energy systems, so this requirement will increase its relevance in the future.
- Dimensions reduction is usually a customers' preference and helps to substitute the breakers while reusing old switchgears with the addition of adapters.

Both external stakeholders and sustainability-oriented:

- Zero downtime: availability is a priority for many customers. The breaker must be in function for 24/24 hours. That also means "time that the product operates without failure (MTBF, Mean Time Between Failures) plus the time required to repair it (MTTR, Mean Time To Repair)", it involves therefore both sustainability and performance.
- Energy efficiency: industry-specific performance requirement with a huge impact on environmental sustainability.

Sustainability-oriented NFRs:

- Ability to provide sustainability insights to supersystems: the ability to provide certifications and precisely measuring the environmental impact is essential in the

	Stakeholders NFRs	Cost-effectiveness	Ensure carry-over	Standard and regulations adherence	Connection to supersystem	Dimensions reduction	Zero downtime	Energy efficiency	Ability to provide sustainability insights to supersystems	Material sustainability	Maximize product lifetime and value utilization within the economy	Social sustainability	Total	%
Internal Stakeholders NFRs	Cost-effectiveness	X	1	0	1	1	0	1	0	1	1	1	7,00	13%
	Ensure carry-over	0	X	0	1	1	0	0	0	0	0	1	3,00	5%
	Standard and regulations adherence	1	1	X	1	1	1	1	1	1	1	1	10,00	18%
External Stakeholders NFRs	Connection to supersystem	0	0	0	X	0	0	0	0	0	0	0	0,00	0%
	Dimensions reduction	0	0	0	1	X	0	0	0	0	0	1	2,00	4%
External + Sustainability	Zero downtime	1	1	0	1	1	X	1	1	1	1	1	9,00	16%
	Energy efficiency	0	1	0	1	1	0	X	0	1	1	1	6,00	11%
Sustainability-Oriented NFRs	Ability to provide sustainability insights to supersystems	1	1	0	1	1	0	1	X	1	1	1	8,00	15%
	Material sustainability	0	1	0	1	1	0	0	0	X	1	1	5,00	9%
	Maximize product lifetime and value utilization within the economy	0	1	0	1	1	0	0	0	0	X	1	4,00	7%
	Social sustainability	0	0	0	1	0	0	0	0	0	0	X	1,00	2%
													55,00	100%

Figure 5.6: Binary pairwise comparison matrix for high-end customers in 2026.

contemporary market. It also allows customers to compare products and choosing consciously the more eco-friendly one.

- Material sustainability, due to the scarcity of resources, especially critical raw materials as copper or noble metals, that are fundamental for the correct functioning of a breaker.
- Maximize product lifetime and value utilization within the economy: a circular requirement that will be satisfied with the implementation of 10Rs strategies.
- Social sustainability is an emerging requirement that will increase its relevance in the future.

From the combination of the pairwise comparison matrices for the four ranges of customers, it resulted a market priority matrix, that shows the relevance of each of these NFRs for each kind of customer (Figure 4.4).

5.2.3. Phase 2: Components-Sustainability Mapping

This is the phase where the components of Emax3 are analyzed to find what are the sustainability hotspots of the product. The sustainable NFRs considered in this phase are "Material sustainability", "Energy efficiency" and "Maximize product lifetime and value utilization within the economy". The focus on these NFRs is due to their direct influence on the product architecture, while "Ability to provide sustainability insights to supersystems" and "Social sustainability" require solutions that are related to both product architecture and company policies. Moreover "Zero downtime" is an hybrid NFR that has an indirect effect on product architecture.

The main support to perform this analysis was the EPD [106] of the product, but this computational data have been sided by various interviews with different experts on sustainability, energy efficiency and materials of the company ABB. Other than showing the environmental footprint of the product, the EPD and the LCA of Emax3 provided the percentage quantity of materials present in the platform Emax3, based on a total weight of 46 kg. The ACB is mainly made of Steel, Copper, polymeric materials as Polyester and Polycarbonate and an infinitesimal amount of Aluminum and precious metals.

The Global Warming Potential (GWP) referred to a single breaker's lifecycle (cradle-to-grave) and measured in kilograms of CO_2 equivalent emissions, is shown in Table 5.1. The lifecycle phases considered are manufacturing, distribution, installation, use phase and end-of-life. However, the environmental impact of the distribution phase is not depending on the product architecture, but on manufacturing and customers' facilities locations. For this reason, this phase will be excluded from the present analysis. For what concerns the installation phase, the emissions shown in the table are mainly caused by the packaging disposal processes: they will therefore be incorporated in the end-of-life considerations.

Table 5.1: Estimation of the GWP of an ACB based on the newest Emax3 platforms, and measured in kg of CO_2 equivalent.

Category	**Total**	**Manufacturing**	**Distribution**	**Installation**	**Use**	**E-O-L**
GWP	3200 kg	293 kg	53 kg	5 kg	2830 kg	21 kg

Starting from the functional breakdown obtained in Phase 0 (Section 5.2.1), the Bill Of Materials (BOM) of the product and various interviews, a manual mapping of the materials of the main subsystems, their weight and the relative emissions produced has been conducted. This is one of the step that may be automatize in the future, since the datasets of BOM to LCA are already present and they essentially consist in computational operations.

The Table 5.2 shows the CO_2 equivalent emissions linked to the manufacturing phase of the breaker's fixed part. As shown in the table, steel components constituting the fixed part of the breaker have the highest environmental impact of the manufacturing phase, due to their high weight. Copper components such as terminals and jaws have the second higher impact in terms of CO_2 equivalent emissions during manufacturing phase. However, this material is essential for current transfer and the reduction of power losses, so it is unlikely to be substituted in the near future. From the contacts system emissions detail, it results that the noble metals have the highest CO_2 emissions ratio, but they are used in small quantities, that do not influence the total.

	Material	Weight [kg]	Impact [kg CO_2/kg]	CO_2 share [%]
Structural frame	Steel cold-rolled	11,5	4,11	16,12
Contact case	Polyamide 66GF25	0,5	7,35	1,25
Poles frame	BMC GF25	3	4,07	4,7
Handles and levers	Polycarbonate GF10	0,4	9,59	1,31
Terminals and jaws	Copper	3,5	12,51	14,94

Table 5.2: Emissions linked to the manufacturing phase of the fixed part, sorted among its components. The share of CO_2 is considered respect to the total kilograms of CO_2 equivalent estimated during manufacturing phase.

As shown in Table 5.1, the use phase is the most emitting phase of the breaker lifecycle. This is due the long lifespan of the product (certified for 20 years) and the energy losses caused by Joule effect during the passage of current. A relevant observation on this impact estimation is that the emissions linked to use phase heavily depend on the customers, and on the energy mix they use. The subsystems that are more responsible for energy efficiency during use phase are the one involved in the main conductive path (Figure 5.7). This comprehends all the components of the contacts system (fixed and moving contacts, copper braids, terminal, blades), but also the components of the fixed part which connect the breaker to the busbars (jaws and terminals). However, 40% of the energy losses are gathered on the main tips of the contacts, 20% on the flexible copper braids and 15% on the blades, while the other components account for just the 25%.

LCA does not account for all the emissions of the use phase. For instance, the emissions linked to spare parts substitutions are difficult to foresee and quantify, hence they are not mentioned in the computation. Maintenance operation, on the other hand, are considered negligible in terms of environmental impact, but if we analyze them from a circular point of view, they help extending the lifetime of components and, in the long term to produce less substitute parts. Being Emax3 a product of 2025, the information about its spare parts request is not available yet, but the info collected for Emax2 can serve as starting point. The most requested spare parts of Emax2 in the European market from the year 2021 to 2025 are:

1. Transparent cover for trip unit
2. Right plate for accessories (MID, Mechanical Interface Device)
2. Accessories cover
3. Trip unit main board

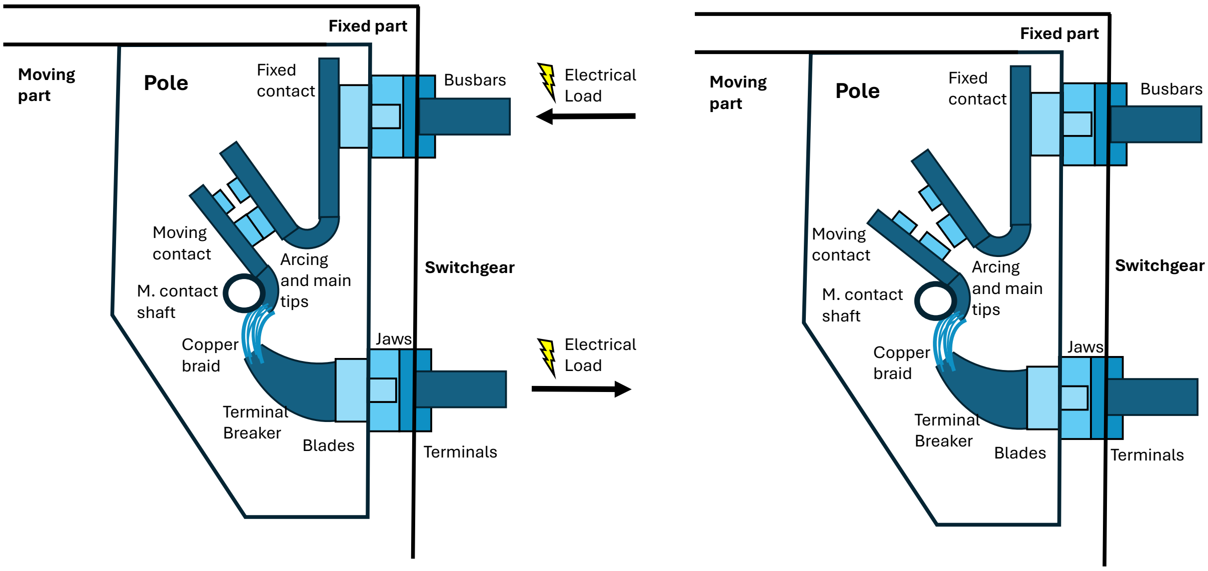


Figure 5.7: Main conductive path of an ACB, schematized. The first figure shows the circuit closed, with the electrical load passing through the switchgears busbars, terminals and jaws. The blades-jaws interface is the first hotspot for power losses, due to it being the interface between the breaker's fixed and moving part. The real contact points between the contacts are the main tips, first cause of power losses, that allow the current to pass to the moving contact, copper braid and lower terminal. The second figure shows the open circuit, without passage of current.

4. Moving part sliding contacts
5. Racked in and out device

For what waste management and end-of-life are concerned, the Point Of Substitution Approach (APOS) defined by ECO passport methodology has been applied [107]. With this approach, recyclable materials recovered the end-of-life of the product are considered equivalent substituted for virgin materials in future production systems. However, this approach to end-of-life is limited, since the possibility of a second life is not taken into consideration. Moreover, the correct disposal of the breaker is under customers' responsibility, and the company cannot control it, unless implementing a take-back service.

Something else that is not examined is the possibility that some components could outlive the breaker. For example, ABB implements the Reuse (R3) circular strategy on the fixed part, since it lasts more than the certified 20 years of the breaker lifespan: this is accounted for in the EPD of the retrofit kit, but there is no mention on the breaker's report. It is safe to say that use phase and the end-of-life are the phases where the 10Rs strategies are the most useful, since they offer solutions to decrease the number of parts failures and fully exploit resources throughout more lifecycles.

The end-of-life of Emax3 will likely happen in 20 years, therefore the emissions linked to this stage are estimated based on the current methods to dispose the constituting materials. From the information collected from the LCA of the product and the standard IEC/TR 62635 [108], the main responsible for the end-of-life emissions are the components made by materials that cannot be recycle, and are disposed in landfills or incinerators. In the Emax3 ACBs series, these materials are BMC (Bulk Molding Compound) and SMC (Sheet Molding Compound), thermosetting polymers materials made of unsaturated polyester, combined with fillers, additives and glass fibers reinforcements. The components made of BMC (or SMC) usually support and protect electrical equipments, for this reason they must be thermal and electrical insulators, while resisting to vibrations and contacts collisions. To increase the stiffness of components, the materials in Emax3 are reinforced by glass fibers, even though they make the components difficult to recycle [109].

To sum up, the hotspots for sustainability identified during the components-sustainability mapping operation are:

For "Material sustainability":

- Structural steel components of the fixed part for the manufacturing phase (Figure 5.8);
- Polymeric-reinforced materials (BMC, SMC...) for the end-of-life.

For "Energy efficiency" all the components related to power losses during use phase, especially:

- Contacts main tips;
- Flexible copper braids;
- Blades.

For "Maximize product lifetime and value utilization within the economy" all the components where one of the 10Rs strategies could be applied, that means:

- Components that are often substituted;
- Components that last more than the breaker, for which a second-life opportunity should be considered

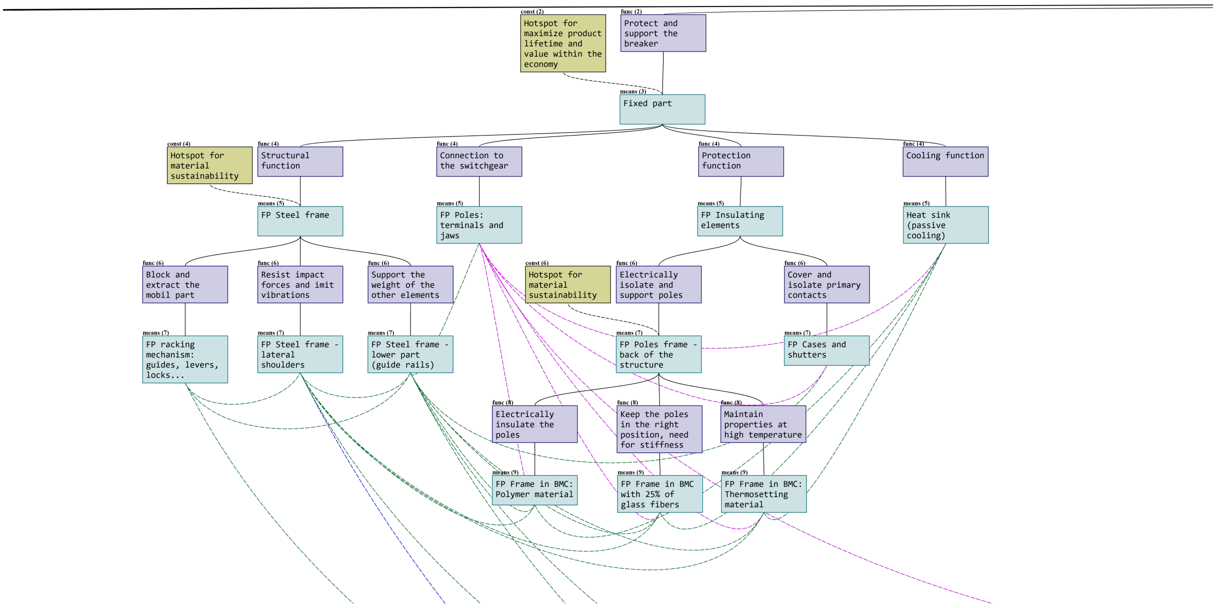


Figure 5.8: Detailed breakdown of the breaker's fixed part, with highlighted hotspots for sustainability.

5.2.4. Phase 3: Sustainable Solutions Generations

During this phase, sustainable Design Solutions (DSs) are generated to substitute the components that are hotspots for sustainability.

To guide the generation process, the sustainability NFRs are added to the EF-M of the breaker as independent functions. "Material sustainability" can be implemented with two approaches: using less material or increasing the material sustainability. "Energy efficiency" instead, can be solved by reducing the power losses during use phase (Figure 5.10). Besides, "Maximize product lifetime and utilization within the economy" can be satisfied implementing the 10Rs circularity strategies (Figure 5.11). The two figures show the sustainable solutions generated to answer the new sustainability-oriented NFRs.

For each of the hotspots defined in Section 5.2.3, the generation of new DSs is essentially guided by two questions:

1. What are the functions of the component? This question entails a detailed breakdown of the component, to understand exactly what part is responsible for each function.

2. What should we modify to remove this interface? This question involves the components surrounding the hotspots for sustainability and leads to the analysis of their interactions.

Material sustainability

The hotspots identified for the NFR "Material sustainability" are the steel frame of the fixed part for the manufacturing phase and the components in glass-fiber reinforced polyester for the end-of-life.

The structural steel frame of the fixed part supports the other elements of the breaker and provide torsional and bending stiffness. As we can see in Figure 5.9, this component can be broken down according to its functions, obtaining:

- Racking mechanism (levers, handles...): the function is to allow the extraction of the moving breaker.
- Lateral shoulders, as they contribute to limit vibration and absorb forces deriving from the contacts collision.
- Lower part (guide rails): it supports the weight of the other elements.

The heavy contributions of structural shoulders to CO_2 emissions during manufacturing phase is linked to their weight, for this reason the sustainable solution proposed is a lightweight design of the component. The synergies between design for sustainability and lightweight design are highlighted in different studies [110], and some of them involve the design of high-voltage breakers [111]. It would be feasible to implement a similar architecture on Emax3 as long as it still satisfies the standard IEC 60947:2020 [87], according to which each modification should maintain the insulation of breakers. However, the problems that could raise from the adoption of a lightweight material in the shoulders design involve the recyclability of the composites, that should be optimized along with the component weight [112]. In this case, the parts to thin would be the lateral shoulders of the structural frame, as they account for 6 kg, on a total weight of 46 kg for the entire breaker.

The sustainability hotspots for the end-of-life of the breakers are spread across different components and are the parts constituted by BMC or SMC materials. These components usually support the electric poles (Figure 5.9) or the contacts, it is therefore necessary that they are electrical insulators. Their supportive function requires that they have elevated stiffness and high thermal stability, because the components belonging to the conductive path are usually heated. In the current architecture, the polyester resin that is the base for BMC or SMC serves as insulator, while the inserted glass fibers increase the components stiffness. Moreover, the thermosetting nature of BMC keeps the mechanical properties of the material constant at high temperatures. The problem with BMC recyclability comes from the insertion of glass fibers, that are the elements that the sus-

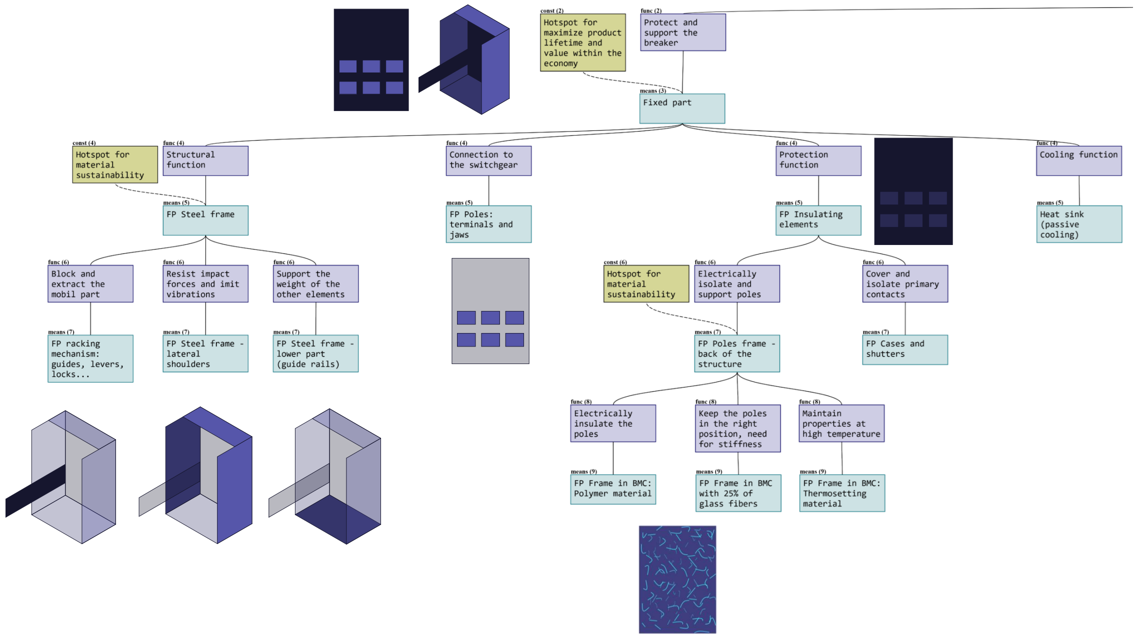


Figure 5.9: Detailed breakdown of the fixed part, with images representing the components involved in each function.

tainable solutions will replace. Therefore, the function assigned to the new solutions will be to increase the stiffness of the polyester, and this is possible by designing an external steel reinforcement or by substituting the glass fibers with natural recyclable ones. The studies about BMC and SMC recyclability and natural fibers are various [113–116], but they present the downside of absorbing water: whenever implemented, they would require additional humidity-resistance treatments.

Energy efficiency

Energy efficiency is an industry-related performance NFR and it is one of the main focuses of ABB. The hotspots for this particular NFR are objects of a continuous internal research to optimize the energy management and reduce power losses, for this reason, the alternative solutions found involve disruptive technologies, that will probably be studied in the future. The hotspots for "Energy efficiency" belong to the breaker's conductive path and are the contacts main tips, the flexible copper braids and the interface between blades and jaws.

For what concerns contacts main tips, new materials are always researched and tested by ABB to ensure the optimal energy management [117]. Another ABB's expedient to reduce power losses, is to compensate contacts wearing by modifying their position. To

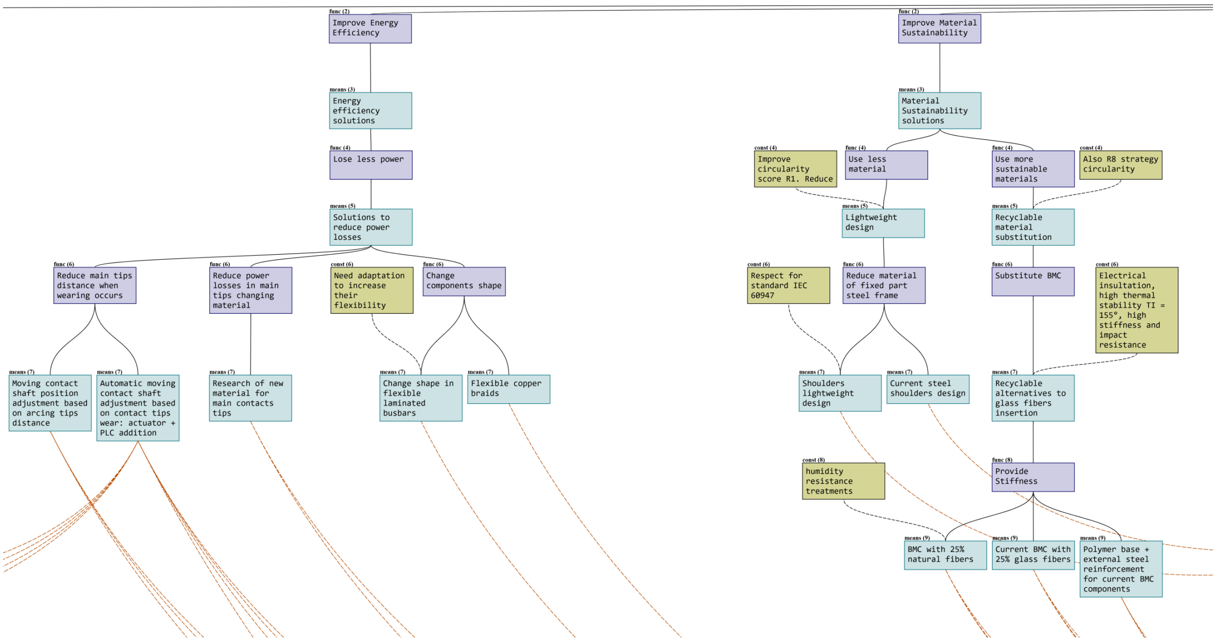


Figure 5.10: Design Solutions for "Material sustainability" and "Energy efficiency" NFRs.

achieve so, ABB's operators measure with a feeler gauge the distance between the contacts arcing tips and, if it is less than a certain value, they adjust the moving contact shaft accordingly. An alternative to this operation could be the implementation of an automatic contacts pressure compensation system, made of an actuator and ruled by an additional electronic control unit. However, this solution would be difficult to implement, since it would modify various interfaces inside the breaker.

Flexible copper braids allow the contacts movement and current transfer, but their particular shape (Figure 5.7) generates power losses, due to them being full of air. For this reason it could be useful to change their shape in laminated busbars, that are proven to reduce power losses, even though they are less flexible [118]. Another solution to reduce power losses could be changing the interface between blades and jaws, but this would require a significant technological progress.

Maximize product lifetime and value utilization within the economy

The maximization of product lifetime and value utilization is the most intuitive NFR to find solutions for, since it is supported by the 10Rs strategies, that serve as prompts and guidelines.

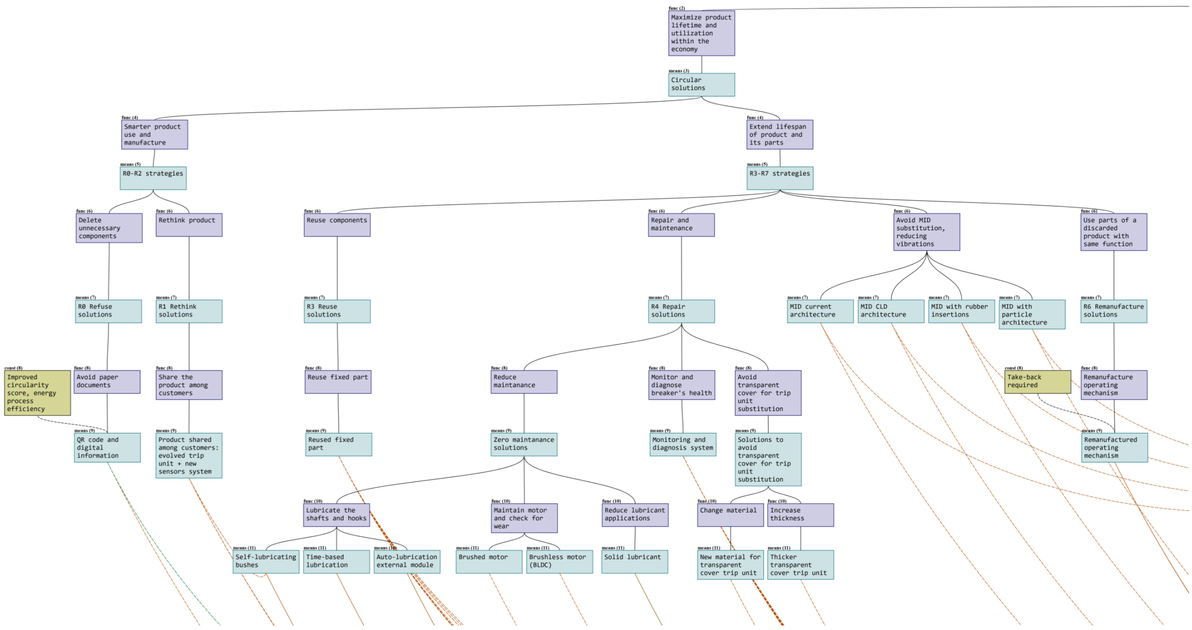


Figure 5.11: Design Solutions for "Maximize product lifetime and utilization within the economy" NFR.

Proceeding in order we find R0 (Refuse), R1 (Rethink), R2 (Reduce), R3 (Reuse), R4 (Repair), R5 (Refurbish), R6 (Remanufacture), R7 (Repurpose), R8 (Recycle) and R9 (Recover). However, Recycle (R8) and Recover (R9) will be excluded from the present analysis, since they overlap with the NFR "Material sustainability", that has already been considered.

Refuse (R0) strategies could seem like the most difficult to implement, since we are used to consider each of the products' components essential, but have the highest circularity potential. For example, different documents with the instructions for assembly and maintenance are delivered with Emax3 breakers, and this could be avoided in favor of a QR code imprinted on the structural frame.

Rethink (R1) strategies modify the thought behind the product and they usually promote product-as-a-service approach. ABB's Emax3 architecture is already suitable for this type of approach, since it is at an advanced digitization stage. The criticalities for this strategy mostly concern cyber-security and customers' privacy. Despite this, many studies already mention the transition to product-as-a-service in the electrical manufacturers industry [119–121], also in view of the development of multi-energy systems [122–125].

R3-R7 strategies are focused on product lifetime extension. For example, ABB implements the Reuse (R3) of the fixed parts of disposed breakers, to host the retrofitting kits. Repair

(R4) strategies are equally important for this analysis, since less failures of the components guarantee a reduction in CO_2 emissions during the manufacturing phase of spare parts. This is the category of all the strategies linked to condition monitoring, sensors and also the optimization of maintenance operations. The maintenance operations mainly involve clean and lubricate hooks and shafts and check the status of the components, especially motor brushes and coils. Here, an ulterior distinction is needed: time-based maintenance does not account for breaker activity, while condition-based maintenance is strongly linked to the number of operations performed.

Some solutions implemented by ABB to extend the lifetime of components and reduce maintenance operations are the substitution from a liquid lubricant to a solid one (which needs less applications) and the addition of a monitoring system to check the health status of the breaker. At the moment, an algorithm implemented in the trip unit receives as inputs the number of switching operations (mechanical and electrical) performed and the measurements of temperature, current, humidity from sensors in strategic components, such as coils and the motor, and uses them to predict the remaining useful life of Emax3. However, many studies underline the relevance of a vibrations-based diagnostic system implementation, despite the difficulties linked to their execution. For instance, every breaker is characterized by a unique vibrations range, making it difficult to establish standardized health parameters, and the presence of noise in the measurements (especially in harsh environment) interferes with the extraction of relevant data [126–128].

Another solution to reduce maintenance operations and extend components lifetime could be avoiding time-based lubrication operations, by replacing standard bushes and bearings with self-lubricating ones [129]. The chosen solution among self-lubricating bearings would be the bronze type, with microscopic pores impregnated with oil, which release micro-doses of lubricant during operation [130]. This solution is suitable for low-activity breakers, but not sufficient for high-duty ones, whereas could be worth to consider the implementation of an automatic lubrication system [131]. However, the addition of an external lubrication system could be an overdesign for the amount of lubricant required by low-duty breakers.

In the same way, high-duty breakers could benefit from a more performative motor, to avoid substituting it after 10 years of service due to its brushes damages [132]. It could be worth considering a brushless model, that would also be easier to monitor, since its standardized vibrations range, but this solution could represent an overkill for low-duty breakers requirements [133].

The most intuitive Repair (R4) solutions are linked to the lifetime extension of components that are substituted more often: this comprehends the right plate for accessories (significant example of Section 4), the transparent cover for trip unit and the sliding contacts. For what concerns the transparent cover for the trip unit, the substitutions happen because it is a thin and fragile component, that is often damaged by transportation phase. To extend its lifetime, a change of material or a thicker shape could be considered.

The sliding contacts are part of the interface between moving and fixed part, and they are frequently damaged from the insertion and extraction operations of maintenance. A temporary solution to extend their lifetime could be the reduction of maintenance operations, while a more disruptive one could be changing the whole interface between moving and fixed part, where they are inserted. In fact, the configuration of Emax3 as extractable breaker is an established technological solution that allows to change the moving part of breaker without modifying the switchgear. However, this configuration employs more resources than the integrated one, for example a bigger quantity of copper that constitutes the electrical interface between fixed and moving part and the energy losses due to the jaws-blades interface. Reconsidering this configuration, especially the interface between blades and jaws and the one between fixed and moving sliding contacts would be beneficial for the breaker sustainability, but it requires a progress of the current technological knowledge.

To implement one of the strategies among Refurbish (R5), Remanufacture (R6) and Repurpose (R7), the company should establish a take-back service, otherwise they could not be applied regardless of the product architecture. However, more and more customers are starting to require this service, so it could be useful to think about the components or subsystems that outlive the breaker. In the breakers which perform few operations a year, the system who could be remanufactured is the operating system, without big modifications at its current architecture.

5.2.5. Phase 1*: Customers segmentation review

During the phase of sustainable solutions generations (Section 5.2.4), a distinction in the breaker utilization raised. As a matter of fact, ACBs installed in data centers and conventional infrastructures perform a limited number of switching operations per years, typically up to few tens. In contrast, breakers employed in renewable energy applications, especially in wind sector, experience several switching operations per day, resulting in thousands per year [134, 135]. This difference in the breaker utilization profile suggests that some solutions could be optimal for low-duty applications, but not suitable for high-duty breakers.

On one hand, high-duty breakers are subjected to frequent components substitutions due to wearing and failures. The environment that surrounds them is often dirty and they are kept in harsh conditions. At the end-of-life, their components are damaged to the point that they can not be reused or remanufactured. On the other hand, low-duty breakers are closed inside clean switchgears and have a static activity. For the number of operations that they perform, some of their components are over-designed in order to comply with standards and regulations, but also to satisfy the high-duty range of customers with a single product. Considering just the low-duty range, a slimmer design of structural elements could be considered, as well as the possibility to reuse or remanufacture the most long-lasting components.

As a consequence, a further customers segmentation is introduced within the high-end market, distinguishing between low-duty and high-duty customers. High-duty customers also introduce a new NFR, namely "Operational endurance", that is the ability to withstand a large number of switching operations without degrading its mechanical and electrical components. This new NFR is considered both sustainability-oriented and required by external stakeholders, since it involves the lifetime extension of the components. In fact, repeated switching cycles accelerate contacts tips wearing, components fatigue and thermal stress accumulation.

The Figure 5.12 shows the binary pairwise comparison of the NFRs relevance for the high-duty range of customers in 2026, with the inclusions of the "Operational endurance" NFR. This requirement is essential for the high-duty range of customers, second only to compliance with standards and regulations. The new priority matrix is shown in Figure 5.13.

At this point, a clarification is needed: customers belonging to the high-end high-duty range usually purchase the Emax3 E4.3 format, while the analysis performed until now estimated plausible data for Emax3 E1.3. The hotspots for sustainability do not change, however, the quantitative data involving weight and dimensions refer to E1.3 and may need to be scaled to adapt this model.

5.2.6. Phase 4: Alternative Solutions Evaluation

During this phase, the alternative solutions to increase Emax3 sustainability (Figure 5.10, 5.11) are evaluated based on their correlations to sustainability-oriented and the other NFRs (Figure 5.13).

The alternative solutions that involve changes in Emax3 architecture are compared in the evaluation grid (Figure 5.14), according to the process illustrated in Section 4.6. Therefore, solutions such as sharing the breaker, reusing the fixed part or remanufacturing

	Stakeholder NFRs	Cost-effectiveness	Ensure carry-over	Standard and regulations adherence	Connection to supersystem	Dimensions reduction	Operational endurance	Zero downtime	Energy efficiency	Ability to provide sustainability insights to supersystems	Material sustainability	Maximize product lifetime and value utilization within the economy	Social sustainability	Total	%
Internal Stakeholders NFRs	Cost-effectiveness	X	1	0	1	1	0	0	1	0	1	1	1	7,00	11%
	Ensure carry-over	0	X	0	1	1	0	0	0	0	0	0	1	3,00	5%
	Standard and regulations adherence	1	1	X	1	1	1	1	1	1	1	1	1	11,00	17%
External Stakeholders NFRs	Connection to supersystem	0	0	0	X	0	0	0	0	0	0	0	0	0,00	0%
	Dimensions reduction	0	0	0	1	X	0	0	0	0	0	0	1	2,00	3%
External + Sustainability	Operational endurance	1	1	0	1	1	X	1	1	1	1	1	1	10,00	15%
	Zero downtime	1	1	0	1	1	0	X	1	1	1	1	1	9,00	14%
	Energy efficiency	0	1	0	1	1	0	0	X	0	1	1	1	6,00	9%
Sustainability-Oriented NFRs	Ability to provide sustainability insights to supersystems	1	1	0	1	1	0	0	1	X	1	1	1	8,00	12%
	Material sustainability	0	1	0	1	1	0	0	0	0	X	1	1	5,00	8%
	Maximize product lifetime and value utilization within the economy	0	1	0	1	1	0	0	0	0	0	X	1	4,00	6%
	Social sustainability	0	0	0	1	0	0	0	0	0	0	0	X	1,00	2%
														66,00	100%

Figure 5.12: Binary pairwise comparison of the NFRs for high-end high-duty customers in 2026.

Priority Matrix		Low duty high-end customers 2026	Low duty high-end customers 2040	Low-end customers 2026	Low-end customers 2040	High duty high-end customers 2026	High duty high-end customers 2040
FRs	Basic needs	must-have	must-have	must-have	must-have	must-have	must-have
Internal Stakeholders NFRs	Cost-effectiveness	12%	9%	15%	14%	11%	8%
	Ensure carry-over	5%	2%	11%	6%	5%	2%
	Standard and regulations adherence	17%	17%	17%	17%	17%	17%
External Stakeholders NFRs	Connection to supersystem	0%	11%	0%	8%	0%	9%
	Dimensions reduction	3%	0%	8%	3%	3%	0%
External + Sustainability	Operational endurance	6%	3%	3%	0%	15%	15%
	Zero downtime	15%	14%	12%	12%	14%	12%
	Energy efficiency	11%	15%	14%	15%	9%	14%
Sustainability-Oriented NFRs	Ability to provide sustainability insights to supersystems	14%	5%	6%	2%	12%	3%
	Material sustainability	9%	8%	9%	9%	8%	6%
	Maximize product lifetime and value utilization within the economy	8%	12%	5%	11%	6%	11%
	Social sustainability	2%	6%	2%	5%	2%	5%
		100%	100%	100%	100%	100%	100%

Figure 5.13: New priority matrix with high-duty range of customers.

the operating system are excluded from this analysis. The change of material for the transparent cover for the trip unit and the substitution of the paper documents with a QR code are excluded as well, since they wouldn't modify relevantly the interfaces among components. Finally, the solutions based on conditions monitoring and diagnosing are already being continuously updated by ABB, and the implementation of new sensors and algorithm would involve more the electronic part of the breaker, instead of the mechanical part, that is the object of this analysis.

The selected alternative solutions generated 576 different DSMs, that are ranked based on the positive or negative correlation of their components to customers NFRs.

Among the sustainable solutions:

1. The implementation of a lightweight design for structural shoulders would have a positive influence on the material sustainability, since it would reduce the quantity of waste created. However, lightweight materials are not mass produced yet, and their cost is much higher than steel. The solution would probably become more profitable in the future.

2. The analysis of the possible alternative solutions to the current right plate for accessories (or MID) architecture has already been presented in Section 4.5.

3. For what concerns a possible substitute for BMC (or SMC) materials, two solutions have been considered: BMC with natural fibers and a polymeric base surrounded by an external steel reinforcement. Both these solutions will increase the material sustainability of the product, but at a higher cost. Also, the addition of an external steel structure will increase the dimension of the breaker, while the use of a natural fibers-reinforced material would require additional humidity treatments, increasing its costs.

4. With the choice between the flexible copper bars and the laminated busbars in the conductive path of Emax3, the differences in NFRs satisfaction mainly involve energy efficiency and costs. In fact, busbars are better conductors and would benefit power losses, but this conductivity is due to an higher quantity of copper, that would decrease cost-effectiveness and material sustainability. Moreover, busbars are less flexible than braids, probably conducing to more frequent failures and decreasing operational endurance and component lifetime.

5. The addition of an automatic system to adjust the moving contact shaft position according to the arcing tips distance would guarantee the right pressure of the contacts. It would therefore benefit the energy efficiency, downtime reduction and

		HighEnd LowDuty 2026	HighEnd HighDuty 2040	LowEnd 2026	LowEnd 2040	HighEnd HighDuty 2026	HighEnd HighDuty 2040
Internal Stakeholders NFRs	Cost-effectiveness	12%	9%	15%	14%	11%	8%
	Ensure carryover	5%	2%	11%	6%	5%	2%
	Standard and regulations adherence	17%	17%	17%	17%	17%	17%
External Stakeholders NFRs	Connection to supersystem	0%	11%	0%	8%	0%	9%
	Dimension reduction	3%	0%	8%	3%	3%	0%
External + Sustainability	Operational endurance	6%	3%	3%	0%	15%	15%
	Zero Downtime	15%	14%	12%	12%	14%	12%
	Energy efficiency	11%	15%	14%	15%	9%	14%
Sustainability-Oriented NFRs	Ability to provide sustainability insights	14%	5%	6%	2%	12%	3%
	Material sustainability	9%	8%	9%	9%	8%	6%
	Maximize product lifetime and value utilization within the economy	8%	12%	5%	11%	6%	11%
	Social sustainability	2%	6%	2%	5%	2%	5%
		100%	100%	100%	100%	100%	100%

	Current steel shoulders design (1)	Shoulders lightweight design (2)	MID current architecture (3)	MID CLD architecture (4)	MID with rubber insertions (5)	MID with particle architecture (6)	BMC with 25% natural fibers (7)	Current BMC with 25% glass fibers (8)	Polymer base + external steel reinforcement for current BMC components (9)	Flexible copper braids (10)	Change shape in flexible laminated busbars (11)	Moving contact shaft position adjustment based on arcing tips distance (12)	Automatic contacts pressure compensation system (13)	Time-based lubrication (14)	Self-lubricating bushes (15)	Auto-lubrication external module (16)	Brushed motor (17)	Brushless motor (BLDC) (18)
Cost-effectiveness	9	-9	0	-3	-3	-9	-9	9	-9	9	-9	0	-9	9	-3	-9	9	-3
Ensure carryover	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-9	0	0
Standard and regulations adherence	0	0	0	0	-9	0	0	0	0	0	0	0	0	0	0	0	0	0
Connection to supersystem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dimension reduction	0	0	0	-3	-3	-9	0	0	-9	0	0	0	-3	0	0	-9	0	3
Operational endurance	0	0	0	3	3	3	0	0	0	3	-3	0	9	-3	3	9	0	3
Zero Downtime	0	0	0	3	3	3	0	0	0	0	0	0	9	-3	3	9	-3	9
Energy efficiency	0	0	0	0	0	0	0	0	0	-9	9	0	9	0	0	0	0	0
Ability to provide sustainability insights	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Material sustainability	0	3	0	-3	-9	-3	9	-9	-3	0	0	0	-3	0	0	-9	0	0
Maximize product lifetime and value utilization within the economy	0	3	-3	3	3	9	0	0	0	3	-3	0	9	0	3	3	-3	9
Social sustainability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5.14: Alternative evaluation grid applied to Emax3. The solutions with the gray background represent the current Emax3 architecture, while the white background points at the sustainable alternatives.

operational endurance, other than lifetime extension. However, its criticalities would involve cost-effectiveness, dimensions and material sustainability, since it would need additional manufacturing processes.

6. To correctly maintain the breakers components and extend their lifetime, lubrication is essential. However, the solutions proposed aim at reducing the maintenance operations and lubricating shaft and hooks only when needed. This would be possible by substituting the current bushes with some self-lubricating ones or adding an external automatic lubrication module. Both the solutions would increase the maximization of lifetime, the availability and the operational endurance of the breaker, even though at different levels. Moreover, they would benefit the downtime reduction and the operational endurance. The downsides of implementing these solutions are linked to the costs and, for what concerns the auto-lubrication module, carryover, dimensions and material sustainability.

7. Finally, the substitution of the current brushed DC motor with a brushless model would benefit the lifetime of the component, and would reduce downtime, since it would not require maintenance. Brushless motors also convey higher torques with the same dimensions, the adoption of one of them would then reduce the volume occupied by the component. Its main disadvantage is surely the cost, that could mainly impact low-duty applications, where it could represent an overdesign.

5.2.7. Phase 5: Product Architecture Analysis

The evaluation phase compared and ranked 576 DSMs, and found that the most suitable for both high-end high-duty and low duty customers in 2026 is DSM 461. Low-end customers go from DSM 468 in 2026 to DSM 469 in 2040, while the highest ranked DSM for future high-end low-duty customers is DSM 438, and for high-end high-duty customers DSM 478 (Table 5.3).

Table 5.3: The table shows the highest ranked DSMs for every range of customers and the NFR satisfaction scores associated to every matrix.

Customers' ranges	1^{st} DSM	2^{nd} DSM	3^{rd} DSM
High-end low-duty 2026	N°461; +7,41	N°469; +7,36	N°460; +7,05
High-end low-duty 2040	N°438; +7,41	N°437; +7,23	N°462; +7,23
Low-end 2026	N°468; +6,59	N°469; +6,36	N°444; +5,86
Low-end 2040	N°469; +6,72	N°468; +6,5	N°470; +6,36
High-end high-duty 2026	N°461; +8,54	N°477; +8,27	N°462; +8,09
High-end high-duty 2040	N°478; +9,5	N°477; +9,32	N°382; +9,23

Although the ranking seems to point at five different versions of a single product, these results present many similarities, that will constitute the core platform, and the optimal number of variations will be found through a critical analysis.

Emax3 core platform

From the solutions evaluation resulted a platform common core, that would benefit all the customers ranges considered. For example, the current structural shoulders design is the right compromise between costs and sustainability: the substitution of steel with a lightweight material would be convenient only after a decisive reduction in the production cost.

BMC substitution follows the same line of lightweight architecture: the score is not much inferior to the current material, and the cost heavily influence customers' opinions. If the production cost of the natural fibers reinforce materials decreased, this substitution would almost be immediate.

Despite its slightly higher cost, the adoption of a brushless motor (BLDC) resulted convenient for every range of customers. This would allow ABB to slightly reduce the dimensions of its assembly and increasing the breakers' operations uptime, by avoiding the periodic brushes status check. For the high-duty segments, the substitution with a high-performance motor will avoid the necessary substitution after 10 years of service, therefore extending its lifetime.

An automatic contact pressure compensation system would increase the breaker uptime and energy efficiency, by automatically adjusting the distance among tips in case of contacts wearing. On the other hand, this solution would increase Emax3 dimensions. The automatic contact pressure compensation system would be composed of three parts:

1. A new optic sensor that measures contact wear, since currently it is measured indirectly by an auxiliary contact placed on the right MID, due to the contacts system harsh environment;
2. An electronic control unit that receives information from the sensor and conveys it to the linear actuator;
3. A linear actuator, made of a motor and an endless screw, which adjusts the moving contact shaft position in relation to the wear tips status and guarantees the correct pressure between contacts.

To correctly perform their function, these parts should be integrated in the product architecture as shown in (Figure 5.15): the optic sensor in the contacts system, the control unit in the trip unit and the linear actuator should be placed in the space below the motor group, in order to reach the moving contact shaft behind it. The environmental impact due to manufacturing a new module (about 2 kg of CO_2 equivalent) would be compensated by the emissions spared thanks to the reduction of power losses.

As shown in Figure 5.14, the changes expected for the common platform core come with some disadvantages, that could be further analyzed performing other analyses focusing on the NFRs that were not satisfied.

For what concerns the solutions to increase vibrations damping in the right MID, to change of shape for the copper braids and the type of lubrication system, the highest-ranked DSMs differ in relation to the customers' range considered. This allows to define three platform variants for different ranges of customers: Lean variant (Section 5.2.7), Enhanced performance (Section 5.2.7) and Premium sustainable variant (Section 5.2.7).

Lean platform design

Lean platform variant involves low-end customers and the high-end low-duty customers of 2026. Low-end customers generally prefer the current solutions, as they are the most cost-effective. For example, DSM 468 is the only highest ranked matrix to present MID current architecture. However, it is estimated that by 2040, the interest of low-end customers for sustainability will increase. In fact, the highest ranked DSM for low-end customers of the future presents the addition of a viscoelastic layer (CLD) to the right plate for accessories.

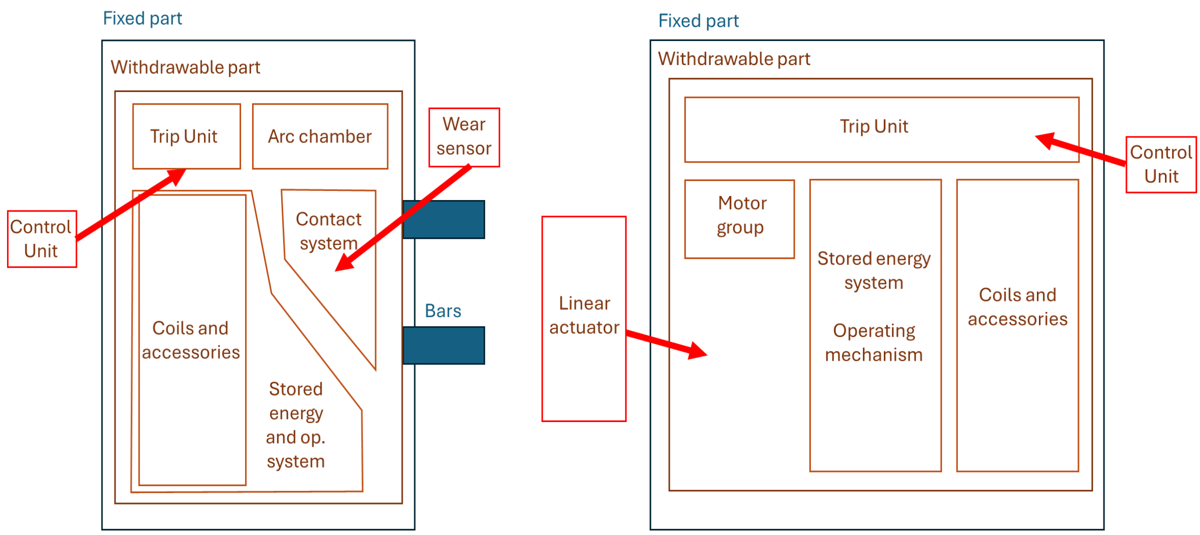


Figure 5.15: Integration of the automatic contacts pressure compensation system in Emax3 E1.3 block architecture. The first figure show the breaker's lateral view, while the second figure shows the product front, with an estimation of the volume occupied by the main subsystems and the eventual pressure compensation system addition.

This is also the MID preferred solution for high-end low-duty customers of 2026 (DSM 461), for this reason this should be the solution implemented in the lean platform variant.

On the other hand, changing the shape of copper braids into laminated bars is so much expensive, that its sustainable benefits are not enough to implement it in the lean platform variant. In this case the preferred solution is keeping the current shape.

For what concerns lubrication, low-end customers of both 2026 and 2040 are satisfied with the current time-based lubrication. However, the implementation of self-lubricating bushes is the preferred option for the high-end low-duty range (DSM 461), since it is slightly more expensive, but it automatically releases lubricant, without interrupting breakers activity. However, the lean platform variant is especially focused on costs, so the preferred solution will stay the time-based lubrication.

After these consideration, the most suitable product architecture of the lean platform variant is DSM 469 for all the low-end customers and high-end high-duty customers of 2026.

Enhanced performance platform design

High-end high-duty customers are the ranges with highest scores in the DSMs ranking. Both of them prefer the current copper braids shape, however, the differences that their highest ranked DSMs present are the lubrication system and the MID architecture.

Since they present the same second-ranked DSM, with scores beyond 8, the enhanced platform variation for these ranges is DSM 477. This product architecture presents the MID with additional damping provided by the CLD method and an external autolubrication module, that enhances their operational endurance.

The additional autolubrication system would be composed by a pump with integrated reservoir and a distributor block to bring the lubricant to hooks and shafts. The pump would be electrically activated periodically, and would pump the lubricant through hoses and nozzles to the elements of the operating mechanism. Figure 5.16 shows where the module will be integrated into Emax3 E4.3 architecture, between the left structural shoulder and the motor group, in order to easily reach the operating mechanism' hooks and shafts, and the volume that it should occupy inside the breaker. Figure 5.17 instead, shows a preliminary concept of the autolubrication module, with blocks that represent its components, to give a general idea of the system configuration. The dimensions of the breaker are different than the ones shown in Figure 5.15, because the addition of an automatic lubrication module will involve just the high-duty range of customers, and will refer to Emax3 E4.3 dimensions, the format purchased by the companies in the wind and renewable sector.

To manufacture a similar system, about 3 kg of CO_2 equivalent would be produced, however lifetime of shafts and hooks would extend. The detailed environmental assessment of this solution would require a complete LCA, also considering the use phase of the module and a possible second life after the breaker's disposal. However, this is a preliminary concept definition phase, which highlights the possible benefits of the presented solutions, while postponing more detailed analysis of the most promising changes.

Premium sustainable platform design

High-end low-duty customers of 2040 distinguish themselves from the other ranges due to a higher interest in sustainability, rather than costs. DSM 438, the highest ranked matrix for their range, presents expensive solutions like the substitution of copper braids in favor of laminated busbars, the redesign of the right MID to obtain a particle architecture and the choice of self-lubricating bushes and bearings to reduce maintenance operation.

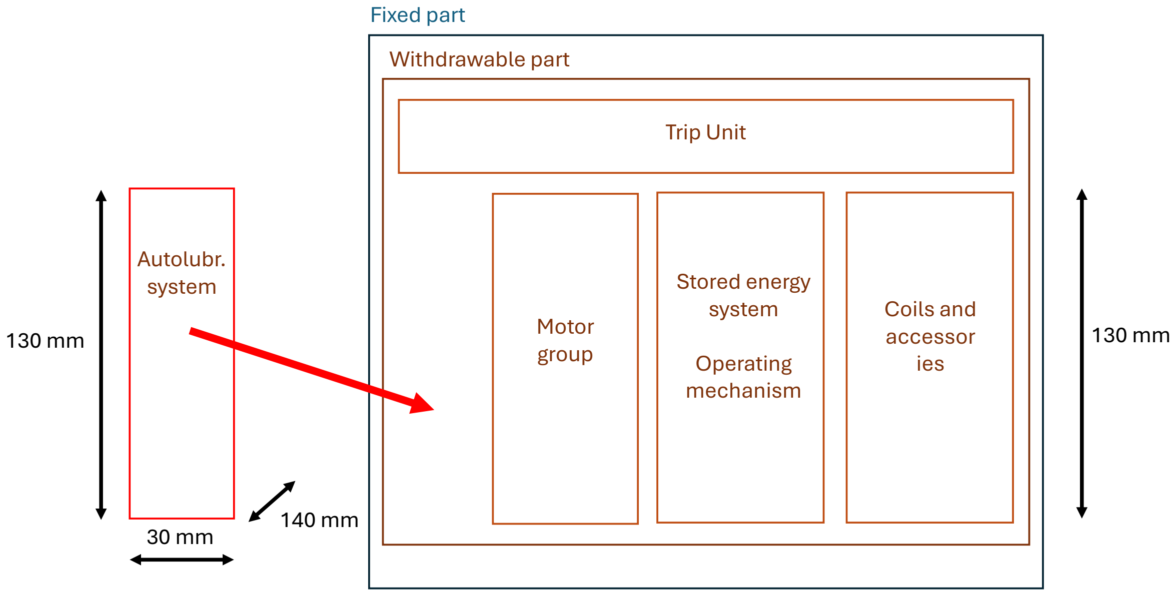


Figure 5.16: Integration of the autolubrication module in Emax3 E4.3's architecture. This figure shows the front of the breaker and an estimation of the volume that the autolubrication module would occupy. The depicted position would ensure lubrication to operating mechanism's shafts and hooks.

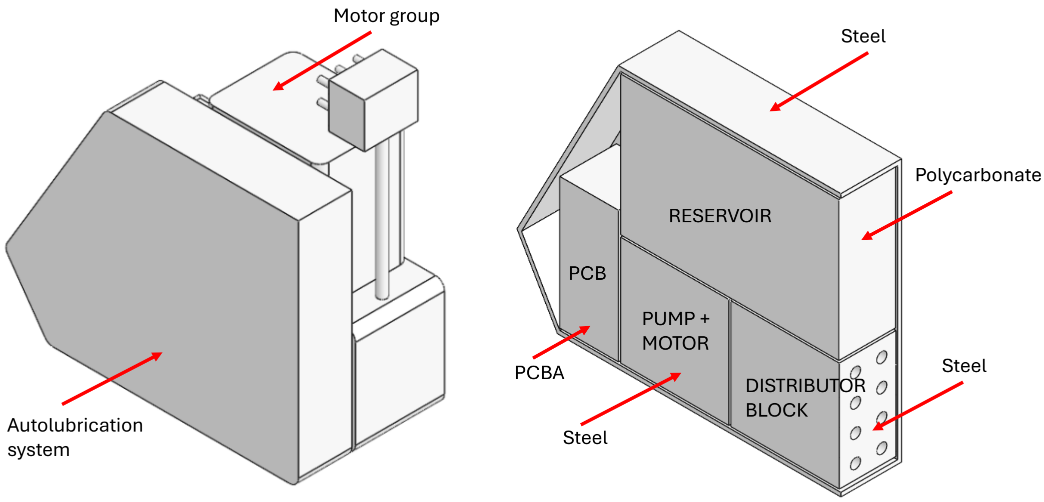


Figure 5.17: Preliminary concept for the autolubrication system, complete of estimated materials and volumes with respect to the motor group. With this configuration, the lubricant would be pumped to the distributor block and then to the operating mechanism's shafts and hooks through tubes and nozzles, connected to the distributor block.

At the moment, these solutions are not economically sustainable to implement for the mass, however, they could constitute a premium sustainable platform variant to implement on demand. In the future, it is possible that some of these solutions will become more affordable and this platform variants could become mass-produced.

Final architecture

Emax3 final architecture is brought back into the EF-M model form, that now presents sustainability requirements among its functions. Figure 5.18 shows how the sustainable solutions are integrated into the architecture of the accessory module, operating system and lubricating elements. It is important to notice that the solutions included derive from both the evaluation performed in Section 5.2.6, and the solutions already implemented by ABB. This inclusion allows a comprehensive overview on the sustainability strategies implemented on Emax3, in order to easily modify them again in the future.

Some of the new sustainable solutions belong to different platform extensions. For example, the right plate for accessories (MID) presents a CLD architecture for the Lean and Enhanced Performance variants and the particle architecture for the Sustainable Premium platform variant. The DSs belonging to different platforms are marked with the "Incompatible" interface to maintain the number of alternative DSMs equal to the number of platform variants (Figure 5.19).

For what concerns the sustainable solutions:

- The addition of an automatic contacts pressure compensation system will increase the energy efficiency of the breaker, allowing to spare the power losses due to contacts initial wear and extending tips lifespan. It is important to remark that power losses are about 30% higher in case of contacts main tips wearing. Moreover, the automatization of this solution will reduce downtime and maintenance operation to manually adjust their position, leading to seamless breaker's operations. However, it will result in an addition of about 2 kg of CO_2 equivalent emission in the manufacturing phase of the product.
- The substitution of the current DC motor with a brushless model will contribute to reduce maintenance operation, since the brushes are one of the elements that need periodic inspections. Its smaller dimensions will allow to use less material and in case of frequent repeated operations, the adoption of this motor model will spare the emissions linked to the manufacturing phase of a new one, since brushed motors are substituted after 10 years of operations.

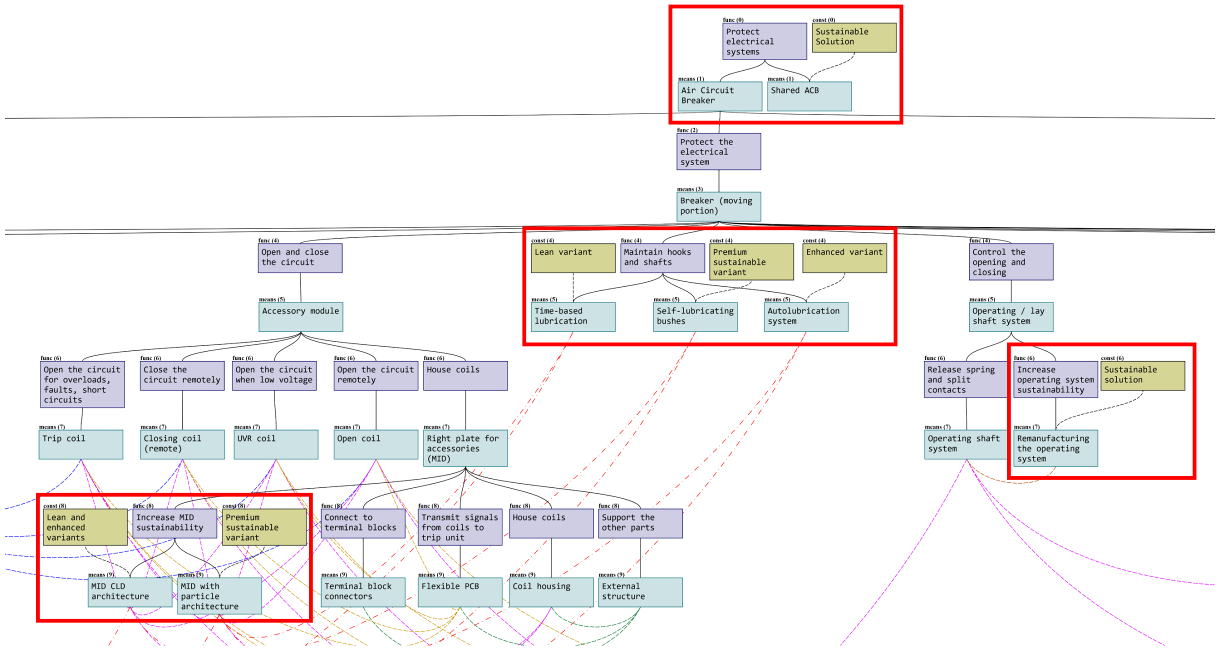


Figure 5.18: EF-M of the final architecture of the accessory module, operating system and lubricating elements, with the integration of the sustainable solutions. It is important to notice the presence of both new DSs (MID new architectures), but also sustainable solutions already implementable with the current architecture (sharing the breaker and remanufacturing the operating system).

- The addition of damping layer to the right MID (both viscoelastic and with a particle architecture) will extend the component lifetime, resulting in fewer downtime linked to substitutions and, in terms of environmental impact, sparing the emissions connected to manufacturing the spare parts.
- For what concerns the "Enhanced performance" platform variant, the integration of an additional autolubrication system will contribute extending the lifetime of shafts and hooks. Its benefits are more difficult to quantify at this stage of product design, but it will serve as starting point for an in-depth analysis during detail design phase.
- Finally, for the "Premium sustainable" platform variant, the solutions will allow to increase energy efficiency, by retrieving part of the power dissipated by the copper braids, that amount for about the 20% of the 2800 kg of CO_2 equivalent emitted during use phase. In addition to this solution, maintenance operations would be reduced by the employ of self-lubricating bearings and bushes, and the breaker's uptime would increase.

The reduction of maintenance operations may not seem directly connected to the product's

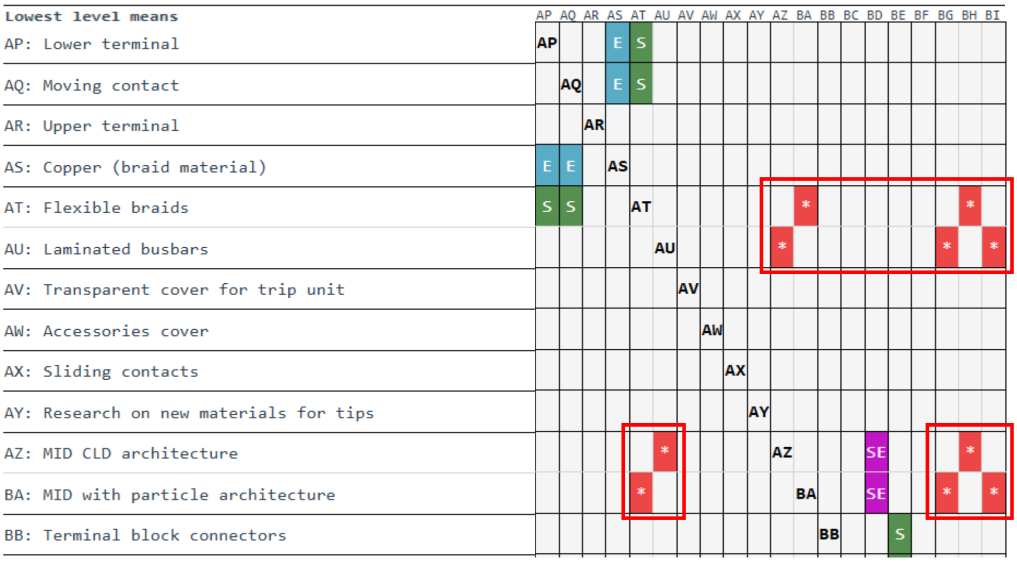


Figure 5.19: Part of the final DSM of Emax3. Here, the solutions belonging to different platform variants are marked with the "Incompatible" interaction. For example, flexible copper braids are part of the "Lean" and "Enhanced Performance" variants. For this reason, they are marked as "Incompatible" to the MID particle architecture, that is part of the "Premium Sustainable" variant.

environmental impact. However, even not considering the emissions linked to technical assistance, the reduction in the extraction and insertion operations of the breaker would be beneficial for the lifetime extension of components such as the protective covers of trip unit and accessories, and sliding contacts, that are one of the most purchased spare parts due to the damages caused by transportation and maintenance operations.

Moreover, even if some of the sustainable changes are not economically convenient to implement now, such as a lightweight material adoption for structural shoulders or a natural substitute for glass fibers in BMC materials, these ideas could be useful in the future, when the production quantities will increase and the costs will reduce. In fact, one of the advantages for the adoption of this methodology is the generation of a comprehensive sustainability overview, which collects past (ABB's initiatives), present (sustainable changes applied) and future solutions all in the same design space.

At this stage of the design process it is difficult to precisely estimate the CO_2 equivalent kilograms that the implementation of these solutions would spare. However, the benefits of reducing even slightly power losses and sparing the emissions of producing new spare parts for motors, right plate for accessories and sliding contacts are unquestionable.

6 | Discussion and future developments

This chapter will present the validation of the methodology and the discussion of strengths and weak points. Moreover, possible future developments will be illustrated and analyzed.

The present thesis proposed a methodology to integrate sustainability into product platform design. During this operation, sustainability is addressed comprehensively, by combining LCA-based analysis and the circularity strategies framework of 10Rs, to identify the main product hotspots to detail and possibly modify through some sustainable solutions. The methodology allowed to perform a MDA of the solutions, by evaluating them with regard to all the stakeholders' NFRs, obtaining a trade-off among sustainability and the other requirements.

The methodology applied to the sustainable redesign of an ACB allowed to increase the product sustainability, by implementing new design solutions. The ACB chosen as case study is ABB's Emax3 series and the sustainable solutions generated involved lifetime extension of different components, and strategies to increase energy efficiency and material sustainability. The highest ranked DSMs resulting from the analysis constituted three different variants of the core product platform, distinguished based on the degree of implementation of sustainable solutions.

The sustainability-oriented NFRs considered during the application of the methodology to the breaker were strictly related to environmental sustainability. Social sustainability is another pillar of sustainability and ABB's approach to the topic, but it was not the focus of the analysis due to its strong dependence on company policies, that are not modifiable from the product architecture representation. However, a topical example of the relation between product architecture and social sustainability is the presence of noble metals inside the breaker, that depends strongly on the geopolitical uncertainty surrounding the supply of critical raw materials[1]. Studying how the products architecture influence social sustainability (and vice versa) is complex interesting aspect that needs to be further

[1]European Commission's webpage about Critical Raw Materials Act.

investigated in the future.

The enabling tool Trinity Systems Modeling has been used to implement the methodology application to the industrial case. Trinity allows designers to compute EF-M models and automatically extracts the corresponding DSMs, with the opportunity to export both the Master DSM (the matrix which presents all the alternative solutions, even if incompatible among them) and the individual designs (every possible combination of the compatible DSs). Once exported the matrices, the ranking operation is performed by a Python code, that allows to identify the most suitable product architectures.

The validity and results of the methodology have been assessed periodically during weekly reviews, where the feasibility and the costs of the sustainable solutions implementation has been evaluated in relation to their environmental impacts. In the last meeting, the whole methodology process was reviewed to identify its strong and weak points. One of the strong points emerged is the inclusion of sustainability in the early design stages. This represents the present and future development of sustainability methodologies, because an early integration allows designers to simultaneously control product functionalities and sustainability in a single design space. Moreover, the sustainability-oriented platform methodology provides decision-making support, by evaluating the benefits of sustainable solutions with regard to their impact on the other NFRs.

On the other hand, some downsides of the methodology implementation involved the necessity of performing the operations with different tools, by exporting and importing files and information. One of the future development of the methodology should be the automatization of various stages in a dedicated digital environment. Trinity is an intuitive tool, but limited for what concerns DSMs evaluation, that must be performed through external coding. It would be useful to develop a structured tool, which allows to handle the whole product architecture representation in the same space, to allow the passages from the individual DSMs to the EF-M models and, in particular, that autonomously perform the DSMs ranking and classification. In this way, the final product architecture could be computed automatically. Another characteristic of the new tool should be cybersecurity: the data inserted by designers may be sensible and should be protected.

Moreover, future developments will involve AI integration to support manual operations, that are currently various. For example, requirements identification phase could be supported by recent AI algorithms, that automatically scan customers' needs and classify them into needs, requirements and solutions [100]. Another step which could benefit AI integrations is the generation of new DSs: it could be useful to follow Kwon et al.'s example [136], which explained how image recognition can be used by automatic algorithms to look for repurposing solution in the automotive sector.

These are necessary future changes to enhance the scalability and efficiency of the methodology, but its application was met with approval and defined as one of the future developments for the company's sustainable design.

Conclusions

In the contemporary market, manufacturers of the products used in the energy sector must satisfy both FRs and NFRs to answer customers' expectations. To produce successful products, the established product platforms development methodologies must provide MDA guidelines to determine their optimal extents, and manage emerging needs like sustainability.

Sustainability is a need of increasing relevance in the energy sector, as the companies in it are subjected to strict regulations and waste reduction policies; for this reason, it is important to integrate it from the beginning of the platform design stage. The present thesis proposes a sustainability-oriented platform design methodology, that integrates the two subjects with MDA and supports decision-making processes from the early product design stages.

For what concerns the approach to sustainability, the present work illustrates how sustainability NFRs that are mutually exclusive and cover all the aspects of product sustainability can be identified and later included in the platform development. This is possible, by integrating information deriving from LCA-based analyses and circular strategies, such as the 10Rs framework. In this way, a general overview of the sustainability opportunities for the product design is available since the early stages.

To develop the methodology for sustainability-oriented platform design, case study research has been carried out during eight months of work-shadowing activity in the R&D headquarter of the company ABB SACE. This research approach guaranteed the access to products technical documentation and workers knowledge and perspective, through the conduction of semi-structured interviews.

The presented methodology starts with the functional decomposition of the product to (re)design and rebuilds it focusing on the sustainability hotspots highlighted during the mapping phase. In the next phase, sustainable solutions are generated to modify or substitute the hotspots, and evaluated based on all the previously identified customers' NFRs. In this way, a new product architecture is produced and can be analyzed again focusing on new NFRs, until finding the optimal configuration.

To implement the methodology, the present thesis relied on the use of EF-M models and DSMs, that supported this integration and fostered the evaluation of alternative sustainable solutions. The manual implementation of such methods has been explained, but future developments will include AI integration to identify requirements and generate and evaluate sustainable solutions.

The design case of an ACB was used to show the implementation of sustainability strategies to minimize the environmental impact of some of its components. The guidelines provided by the present thesis have been applied to an industrial ACB, but will easily adapt to other products and NFRs.

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List of Figures

List of Tables

List of Abbreviations

AC : Alternating Current

ACB : Air Circuit Breaker

AI : Artificial Intelligence

AP : Acidification Potential

APOS : Point Of Substitution Approach

B2B : Business to Business

B2C : Business to Customer

BLDC : Brushless Direct Current

BMC : Bulk Molding Compound

BOM : Bill Of Materials

C : Constraint

CLD: Constrained Layer Damping

CoE : Centre of Excellence

DC : Direct Current

DS : Design Solution

DSM : Design Structure Matrix

EF-M : Enhanced Functions-Means

EPD : Environmental Product Declaration

F-M : Functions-Means

FR : Functional Requirement

GWP : Global Warming Potential

HTP : Human Toxicity Potential

Icu : Ultimate Short-Circuit Breaking Capacity

IEA : International Energy Agency

IEC : International Electrotechnical Commission

KPI : Key Performance Indicator

LCA : Lifecycle Assessment

MDA : Multidisciplinary Design Analysis

MDO : Multidisciplinary Optimization

MID : Mechanical Interface Device

MIM : Module Indication Matrix

MFD : Modular Function Deployment

MCCB : Molded Case Circuit Breaker

NFR : Non-Functional Requirement

ODP : Ozone Depletion Potential

PCB : Printed Circuit Board

SMC : Sheet Molding Compound

Acknowledgements