POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Methodology for sustainability-oriented platform design for circuit breaking technologies

Laurea Magistrale in Mechanical Engineering - Ingegneria Meccanica

Author: Alessandra Lupo

Advisor: Prof. Massimo Panarotto

Co-advisors: Prof. Niccolò Becattini, Luca Lanzoni, Marco Rossi

Academic year: 2025-2026

1. Introduction

To respond to a pressing market environment, manufacturers of power transmission and distribution equipment, such as switchgears and circuit breakers, must satisfy both Functional (FR) and Non-Functional Requirements (NFRs). For instance, breakers must be able to detect and interrupt ground faults (FR), but also be cost-effective and durable (NFRs).

In the energy sector, the demands of customers are usually satisfied through the use of product platforms, sets of common elements, shared among a product family [5]. These platforms increase cost-effectiveness through economies of scale and foster future scalability of the production line by standardizing components. However, platform design focuses on optimizing entire products families [4], often resulting in lack of customization and overdesign, because platforms offer limited components alternatives, that can exceed products actual requirements.

One of the challenges of platform design is to determine the optimal number of variants to balance requirements satisfaction at early design stages. This works well with FRs and costs evaluation, but becomes difficult when dealing with the NFRs linked to sustainability. Sustainability-oriented NFRs are usually integrated later in the design processes, because the environmental data available at early stages are limited [3]. Moreover, sustainability cannot be measured by standardized frameworks as costs and performances yet. In fact, it evolved from computing the environmental footprint of products through LCA-based analyses, to extending products' lifetime and promoting resources utilization through circular strategies as 10Rs [1].

For this reason and since the two subjects evolved independently, the literature presents limited integrations of sustainability and platform design. This is critical for the energy sector, where the need for sustainability is particularly relevant, due to the industry-specific strict regulations and its commitment in pursuing the Sustainable Development Goals.

To support the need to integrate more sustainability into the early stages of platforms development, the present thesis proposes a methodology to develop a sustainability-oriented product platform, that combines LCA analysis with the circular framework of 10Rs from earliest design stages. Moreover, the proposed methodology serves as a decision-making support tool, by evaluating the trade-offs between sustainability strategies and the satisfaction of the other NFRs.

2. Research methodology

The research activity involved case study research on ABB's Emax3 (Figure 1) family of Air Circuit Breakers (ACBs)[1].
Air Circuit Breakers protect the electrical grid, by carrying current and interrupting it when a fault is detected. In normal conditions, 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 the arc chute.

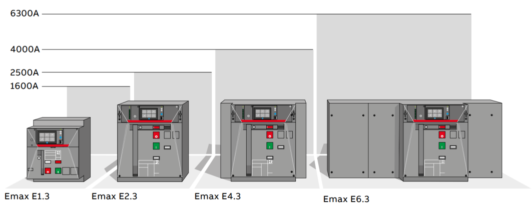


Figure 1: Different models of the Emax3 platform, sorted by frame sizes and rated currents.

The case study approach allowed to investigate in detail the product and its industrial context. The research was performed during eight months of work-shadowing activity in the R&D department of ABB SACE's headquarter, in order to build extensive knowledge about the product and the company processes and decision-making frameworks. The validity of the methodology was evaluated through weekly reviews with company representatives, and a final analysis of strengths, weak points and future developments.

3. Methodology

The methodology to develop a sustainability-oriented platform for an industrial product is made of five main phases (Figure 2):

0. The Preliminary Phase consists in a functional analysis of the product to redesign. To represent the product architecture and the main interactions among subsystems, the methods of Enhanced Functions-Means (EF-M) model and Design Structure Matrix (DSM) are used (Figure 3).
1. Requirements Identification: it follows a market analysis in which customers are characterized and divided into different ranges. Once obtained the market segmentation grid, interviews and benchmark researches are conducted to identify the stakeholders' expectations regarding the product, and it results in a priority matrix of all the stakeholders' NFRs, divided into internal, external and sustainability-oriented.
2. Components-Sustainability Mapping. In this phase, the product is analyzed from the sustainability side, to research the components that have the highest environmental impact or the higher potential for sustainable redesign. The objective of this stage is to highlight and detail the hotspots for sustainability in the EF-M model and DSM.
3. Sustainable Solutions Generation: during this stage, the sustainability-oriented NFRs are added to the EF-M model as new requirements, and new Design Solutions (DSs) are generated to satisfy them. In this phase, the methods of EF-M model and DSM allow to experiment with alternative DSs in the same design space [2].
4. Alternative Solutions Evaluation: the alternative DSs are evaluated based on their correlation to the satisfaction of all the stakeholders' NFRs. The DSs with the highest score contribute to increase the ranking of the DSMs they belong to.
5. Product Architecture Analysis. This is the phase, where the highest-ranked DSMs are analyzed and their DSs integrated into product architecture. The EF-M model and DSM are used to represent it and collect platform variants. It is also the phase where the evaluation results are analyzed and could bring to a new analysis centered on the NFRs not satisfied by the solutions.

The enabling tool used to perform these phases is Trinity Systems Modeling[2].

4. Methodology application

The following section illustrates the application of the methodology to ABB's Emax3 family of ACBs (Figure 1).

[1] ABB's Emax3 webpage

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

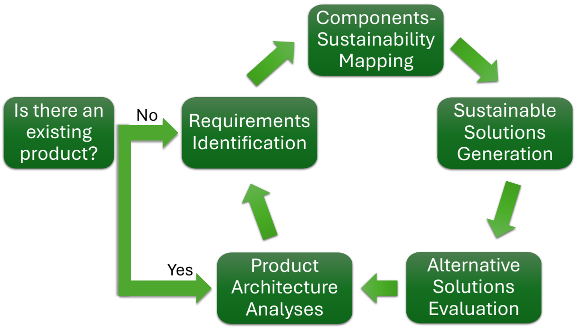


Figure 2: Scheme of the methodology for sustainability-oriented product platform design main phases.

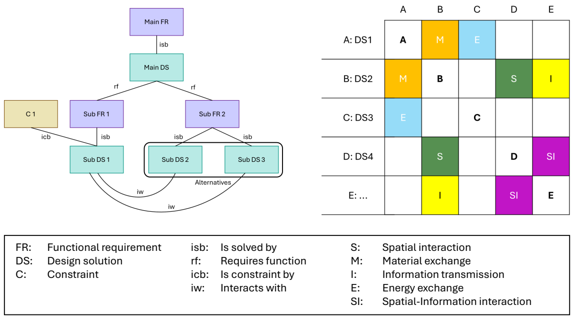


Figure 3: Basic structures of EF-M model and DSM.

4.1. Preliminary Phase

The preliminary phase of the methodology broke down the breaker into 18 subsystems, generating the first EF-M model and DSM. To obtain the decomposition, technical documentation has been consulted and different interviews with company workers have been conducted. This research also produced the product's FRs. The executive summary will focus on one of the subsystems identified during this stage: the accessory module, especially on the right plate for accessories (also called right MID, Mechanical Interface Device), component which supports the coils which open and close the circuit under different fault conditions, and transmit their signals to the trip unit.

4.2. Requirements Identification

The requirements identification phase requires conducting interviews with service and sales experts and analyzing ABB's competitors products, to identify the stakeholders' NFRs.
Figure 4 shows the priority matrix for Emax3 stakeholders. The first column collects the type of NFR considered: if they are requested by the manufacturing company, the customers or if they are sustainability-oriented. The second column shows the list of NFRs identified for the Emax3 platform, while the other columns illustrate the relevance assigned to every NFR by the different ranges of customers. In this case, four ranges of customers were identified, based on the dimension of their companies and the innovation degree of their sectors: low-end and high-end customers, analyzed in 2026 and 2040.

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: Priority matrix for the identified four segments of Emax3 customers.

Other than the NFRs found during the research, "Material sustainability" and "Energy efficiency" were chosen to represent LCA analyses and "Maximize product lifetime and value utilization within the economy" for circularity.

4.3. Components-Sustainability Mapping

For the components-sustainability mapping phase, the documentation linked to the product sustainability has been analyzed and interviews with specialized workers have been conducted.
In particular, Emax3 LCA analysis and the Environmental Product Declaration (EPD) served as a base to identify the components with the highest environmental impact linked to "Material Sustainability" and "Energy efficiency" throughout the product lifecycle. For what concerns the NFR "Maximize product lifetime and value utilization within the economy", the 10Rs circular strategies have been used to identify the components that fail the most and the ones which outlive the breaker, and could maybe be reused or remanufactured.
The analysis revealed that the right plate for ac-

cessories (Figure 5) is an hotspot for "Maximize product lifetime and value utilization within the economy". This small component perform a support function for the coils, and serves as a communication bridge between the coils and the trip unit. The plate (also called MID, Mechanical Interface Device) is one of the most substituted spare parts, because it has to resist vibrations during the breaker's activity and it is solicited by the insertion and extraction of coils during maintenance operations.

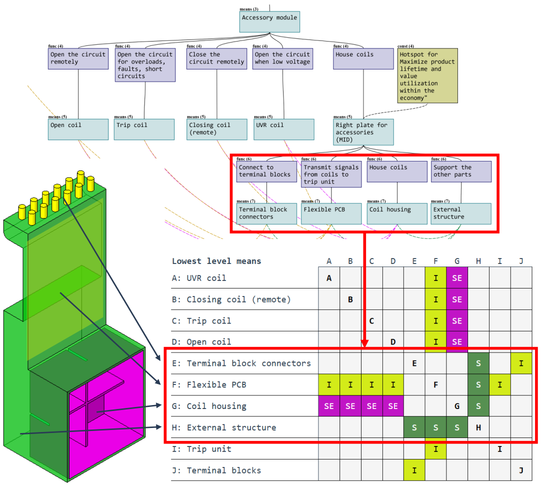


Figure 5: Detail of the right plate for accessories in the breaker's EF-M model and DSM.

4.4. Sustainable Solutions Generation

During this phase, new DSs that modify or substitute the hotspots for sustainability are generate to satisfy the sustainability-oriented NFRs. For example, three sustainable solutions are generated to increase the repairability of the right plate for accessories, extending its lifetime by adding damping layers to its architecture:

1. Additional rubber inserts between the coils and the housing: it would be cost-effective and would extend the component lifetime, but against the standard, since rubber degrades at high temperatures.
2. A viscoelastic layer with the Constrained Layer Damping method (CLD)[3] in the same position: slightly more expensive, but compliant with regulations.
3. A complete redesign of the plate to obtain a particle architecture: best-in-class for what concerns vibrations absorption, but also the most expensive and bulkiest solution.

All these solutions are added to the EF-M model under the new requirement "Maximize product lifetime and value utilization within the economy", and in the product DSM, where the interfaces that will change with the implementation of a new DS are highlighted. For example, an additional layer between coils and coil housing (rubber inserts or CLD) would absorb the vibrations arriving from the breaker, and the coils-housing interface would go from Spatial-Energetic (SE) to Spatial (S). The energetic interaction would move between the additional layer and the two other components (Figure 6).

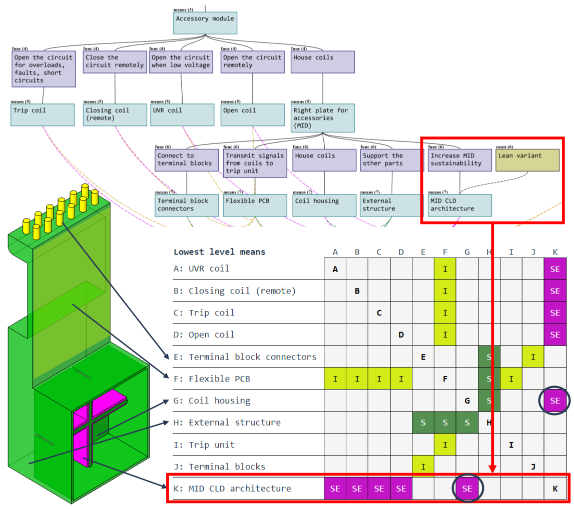


Figure 6: Integration of the sustainable solution "CLD architecture" for the right plate for accessories in the EF-M model and DSM.

For the case of Emax3, the addition of alternative solutions generated 576 DSMs containing every possible DSs combination. However, other than the new solutions, this methodology allows to integrate in the EF-M model sustainable solutions already implemented by the company, such as reusing some subsystems.

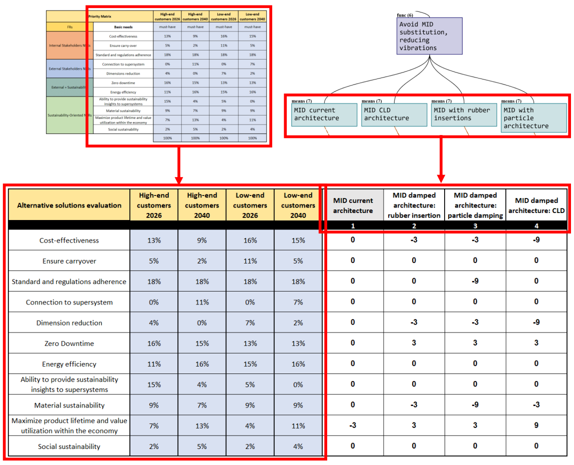
The generation of sustainable solutions for the Emax3 platform raised a distinction in the breaker utilization and, consequently, in the suitability of some DSs. For this reason, it has been necessary to add two ulterior customers ranges: high-duty customers of 2026 and 2040, whose breakers perform several switching oper-

[3] Mechanical engineering technique used to reduce unwanted vibration and noise. It works by interposing a soft, flexible viscoelastic material between a vibrating object and an outer rigid layer.

ations a day, and are subjected to frequent components substitutions due to wear and failures.

4.5. Alternative Solutions Evaluation

This phase aims at understanding what sustainable solution is worth implementing in the product platform. For this reason, an evaluation grid is computed to rate the correlation among the new solutions and the stakeholders NFRs. This scoring system is similar to the Modular Function Deployment method, well documented in literature and in the industry, and consists in assigning high scores to the solutions that satisfy more NFRs and, as a consequence, to the DSMs they belong to. The product most suitable architectures are obtained by exporting the DSMs generated in the previous phase and ranking them with an external Python code, based on the correlation scores of the evaluation grid (Figure 7).



Alternative solutions evaluation	High-end customers 2026	High-end customers 2040	Low-end customers 2026	Low-end customers 2040	MID current architecture (1)	MID damped architecture: rubber insertion (2)	MID damped architecture: particle damping (3)	MID damped architecture: CLD (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 7: The reduced evaluation grid for the sustainable solutions concerning the right plate for accessories and the first four customers ranges.

After performing the evaluation of the 576 DSMs, the highest ranked DSMs for the six ranges of customers were five, but an analysis of their similarities allowed to determine the optimal number of platform variants.

4.6. Product Architecture Analysis

In this phase, the sustainable solutions of the highest-ranked DSMs are integrated into the product architecture. For the Emax3 platform, some of the new DSs were present in every highest-ranked DSMs, but some sustainable changes would only benefit one or two ranges of customers.

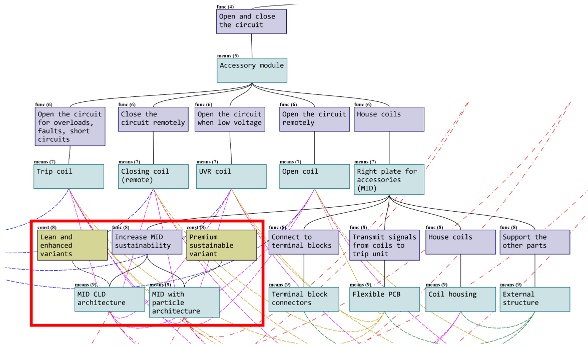


Figure 8: Final architecture of the accessory module, integrated into the product final EF-M. The plate (MID) presents two architecture depending on the platform variant considered.

The analysis and combination of Emax3 highest-ranked DSMs and their solutions produced three different platform variants: Lean, Enhanced Performance and Premium Sustainable. These variants are characterized by the implementation of cost-effective solutions (Lean variant, DSM 459), the prioritization of operational endurance and availability (Enhanced Performance, DSM 477) and the attention to sustainability (Premium Sustainable, DSM 438).
Being the addition of a viscoelastic layer a solution to extend the right plate for accessories' lifetime with a reasonable cost, this solution appears in both Lean and Enhanced Performance variants. Figure 8 shows the integration of the layer in the product final EF-M and DSM.

5. Discussion and future developments

The proposed methodology allows to integrate sustainability into product platform development, by combining LCA-based analyses and circular strategies. Moreover, the methodology allows to evaluate the trade-offs between sustainability and the other identified NFRs (cost-effectiveness, compliance with regulations, availability...), serving as decision-making support.
The application of the methodology to the case study of the industrial family of ACBs assessed the methodology validity, by producing unquestionable benefits to the product sustainability. The most appreciated aspects of the methodol-

ogy were the early integration of sustainability in the design process, and the evaluation of sustainable solutions, based on the other NFRs.
However, future developments involve the development of an integrated tool to handle sustainable platform architectures. The new tool should allow direct transitions from EF-M models to DSMs and internal classifications, and should guarantee the protection of inserted data. Moreover, most of the operations have been carried out manually, limiting the scalability of the methodology: AI algorithms should be included to scan requirements, find sustainable solutions and perform computational activities.

6. Conclusions

Sustainability is a need of increasing relevance, especially in the energy sector, where products are subjected to strict regulations. For this reason, the present thesis proposes a methodology to integrate environmental sustainability into product platform methodologies since early design stages. To ensure a comprehensive approach to sustainability, the present work combines LCA-based analyses with 10Rs circular strategies framework, identifying both the sustainability hotspots and the strategies to reduce their environmental impact.
Other than sustainability, the proposed methodology allows to evaluate the trade-offs with other NFRs, such as performance, costs and compliance with regulations. This is particularly useful in the energy sector, where the customers are highly demanding. In this way, the methodology serves as decision-making support framework, that helps to identify the optimal platform architectures.
The methodology was developed using case study research and was carried out during a eight-months time lapse of work-shadowing activity. The complete application was illustrated through the case of an industrial ACB and resulted in a new platform architecture aimed at reducing its environmental impact.
The implementation of the methodology was supported by the use of EF-M models and DSMs, that fostered the integration of sustainability requirements and the evaluation of alternative 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.
Finally, the methodology was validated through weekly reviews and an analysis of strengths and weak points. Even though the chosen case study was an ACB, the guidelines provided by the present thesis are general enough to be extended to other products, application domains and additional NFRs.

References

[1] Niccolo Becattini, Massimo Panarotto, and Gaetano Cascini. Second life product strategies leading to lca ambiguity: challenges for sustainable design. In *Proceedings of the Design Society*, volume 5, pages 2861–2870. Cambridge University Press, 8 2025.

[2] Julian Martinsson Bonde, Iñigo Alonso Fernández, Michael Kokkolaras, Johan Malmqvist, Massimo Panarotto, and Ola Isaksson. Managing combinatorial design challenges using flexibility and pathfinding algorithms. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, 39, 6 2025.

[3] Julian Martinsson Bonde, Ola Isaksson, Timos Kipouros, Michael Kokkolaras, and Petter Andersson. Exploring design tradeoffs among sustainability, performance, and manufacturability when considering integration of new technologies. In *Proceedings of the Design Society*, volume 5, pages 1635–1644. Cambridge University Press, 8 2025.

[4] Ola Isaksson, Peter Lindroth, Claudia M Eckert, et al. Optimisation of products versus optimisation of product platforms: an engineering change margin perspective. In *DS 77: Proceedings of the DESIGN 2014 13th international design conference*, pages 1947–1956, 2014.

[5] Kevin Otto, Katja Hölttä-Otto, Timothy W. Simpson, Dieter Krause, Sebastian Ripperda, and Seung Ki Moon. Global views on modular design research: Linking alternative methods to support modular product family concept development. *Journal of Mechanical Design*, 138, 7 2016.