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ORIGINAL ARTICLE

Integrating life cycle assessment and design for sustainability for continuous improvement in industrial production systems

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Abstract

Growing regulatory pressure and societal awareness have made sustainability a strategic necessity for industry. However, despite increasing academic research, significant gaps remain between theoretical approaches and their implementation in industrial decision making, where sustainability assessment often serves certification purposes rather than offering continuous improvement. This study proposes a replicable methodological framework that integrates sustainability into corporate design and decision-making processes. The framework includes three main phases: (i) assessment of the current system through Life Cycle Assessment (LCA), (ii) LCA identification of environmental hotspots to define improvement priorities, and (iii) interdisciplinary ideation of circular redesign scenarios using the eco-design approach—a multicriteria, multistage, and multistakeholder systematic process that considers environmental design and development aspects while aiming to reduce adverse environmental impacts throughout a product's lifecycle. The multifunctional team brings diverse expertise, enriches the holistic framework, and enables innovative and creative design proposals while evaluating competing priorities and facilitating trade-offs between life cycle phases. A game-changer has been challenging the status quo, from a conventional design methodology to an environmentally conscious design perspective with emission reduction as the primary core driver. When applied to an industrial case study at ABB S.p.A. on a medium-voltage circuit breaker, the framework proved effective in identifying design modifications that lower environmental impacts without compromising economic or technical feasibility. The results demonstrate the applicability of the Design for Sustainability initiative in promoting continuous product improvement. This methodology fosters an organizational culture that embeds sustainability into industrial innovation across internal ABB business areas and other manufacturing sectors.

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Graphical abstract

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1 Introduction

Environmental sustainability has become a strategic priority across industrial sectors, driven by increasingly stringent regulatory frameworks and rising expectations from customers, investors, and institutions [1, 2]. This shift has encouraged companies to adopt more systematic approaches to sustainability, particularly through product development processes, which largely determine environmental performance [3]. Over the past two decades, the scientific community has developed robust frameworks to support the integration of environmental considerations into different design activities, including eco-design, design for sustainability, and circular design principles. However, eco-design practices frequently rely on specific tools, such as Life Cycle Assessment (LCA) or redesign strategies, without offering decision-ready methods that are transferable across product families [4].

Bovea and Pérez-Belis [5, 6], by providing a taxonomy of eco-design tools, have shown that most existing solutions address only isolated phases of the design process, thereby revealing a methodological gap in the bridging of environmental data with product development decisions. In parallel, Sumter et al. [7] have demonstrated that industrial designers often lack the competencies required for effective integration of circularity principles and therefore reinforce barriers to the operationalization of sustainability in organizations. The available literature also highlights another challenge, as companies often struggle to distinguish between genuinely sustainable design actions and superficial claims. Delmas and Burbano [8], by showing how the persistence of greenwashing practices undermines credibility and complicates the adoption of robust eco-design methodologies, have further reinforced the need for transparent and quantifiable frameworks. Other more recent research has emphasized the importance of linking product design choices with broader business model strategies to enable circularity.

For example, Bocken et al. [5] argue that eco-design becomes effective only when aligned with organizational priorities, cross-functional collaboration, and structured decision making. This past research has prompted a growing body of work on Design for Sustainability (DfS); however, a persistent gap remains between the availability of conceptual frameworks and assessment tools and their effective operationalization within industrial product development processes.

The existing contributions have significantly advanced the theoretical understanding of sustainability-oriented design, ranging from system-level transition perspectives to organizational maturity models and business model innovation strategies. Nevertheless, their application in engineering-intensive industrial contexts often remains fragmented, tool driven, or confined to isolated pilot initiatives [9]. In particular, LCA, although widely recognized as a robust method for quantifying environmental impacts, is used predominantly for ex-post reporting, certification, or compliance purposes in many industrial settings, rather than as an active driver of design decision making and continuous improvement [10]. This limitation is especially critical in sectors characterized by complex products, long service lifetimes, strict safety requirements, and tightly coupled design constraints, such as electrical distribution equipment [11]. In these contexts, sustainability-related decisions must be integrated into existing product development infrastructures and reconciled with technical performance, regulatory compliance, cost, and manufacturing feasibility [12].

To address these challenges, this study proposes a structured DfS methodological framework that explicitly bridges environmental assessment and industrial design practices. The originality of the framework proposed here does not lie in the introduction of new assessment tools; rather, it reveals how existing methods—particularly LCA—can be systematically translated into prioritized, actionable, and decision-ready redesign options suitable for interdisciplinary industrial teams. The framework is characterized by three distinguishing features:

1) It introduces hotspot-driven logic in which LCA results are not treated as static performance indicators but actively used to refine sustainability objectives and focus design efforts on the most influential life cycle stages, components, and materials. This evidence-based refinement enables designers and engineers to move beyond generic sustainability goals toward targeted interventions that have measurable impacts.
2) It adopts an iterative structure that connects the assessment, ideation, and validation phases through a continuous feedback loop. Rather than using a linear progression from analysis to redesign, the process allows sustainability priorities to evolve in response to emerging insights, technical constraints, and design opportunities. This iterative mechanism supports continuous improvement across successive product generations and facilitates knowledge transfer across product families.
3) It is explicitly designed to be embedded within existing industrial product development environments. By leveraging data from enterprise systems (e.g., Enterprise Resource Planning [ERP]), digital design tools (e.g., computer-aided design [CAD]), and LCA software, the methodology aligns sustainability assessment with real-world engineering workflows. This integration enhances replicability and reduces the risk that sustainability remains detached from everyday design and decision-making practices.

Beyond its technical contribution, the proposed framework is unique, as it can be interpreted as a micro-level enabler of broader sustainability transitions in industrial systems. By operationalizing life-cycle thinking within design activities, fostering interdisciplinary collaboration, and supporting evidence-based trade-offs, the methodology contributes to organizational learning and capability building, which are key conditions for advancing circular economy strategies, resilient supply chains, and long-term value creation. In this sense, the framework supports a new shift from cost-centric optimization toward a more holistic, value-oriented design paradigm that incorporates environmental performance as a core decision driver.

The framework proposed here is developed and validated through an in-depth industrial case study conducted at ABB S.p.A., focusing on a medium-voltage circuit breaker [13–15]. The case provides a novel demonstration of how the methodology can be applied in a high-complexity engineering context to identify and evaluate concrete redesign options that reduce environmental impacts while maintaining technical robustness and industrial feasibility. Although the study focuses on product-level improvements, the results highlight additional new opportunities for extending the approach toward upstream supply chain engagement and strategic sourcing decisions.

The structure of the paper is as follows: After this introduction, the second section describes the methods and tools used; the third details the methodology with reference to the case study, highlighting its applicability; and the fourth and final section presents the results and the final discussion.

2 Materials and methods

2.1 Design for sustainability guidelines

The DfS methodology adheres to guidelines based on well-established eco-design principles, international standards, product-specific documents, and regional and market regulations, with the ABB Circularity Framework serving as a primary reference[16, 17]. These frameworks adopt a holistic, life-cycle perspective, ensuring that environmental impacts are assessed from "cradle to grave." All guidelines are accessible via a dedicated Eco-design platform, which also enables the export of specific recommendations in Excel format as a checklist.

This approach provides a structured process for generating and evaluating redesign alternatives during DfS brainstorming sessions. Key tools include Circularity Assessment (CA) and LCA, which benchmark the baseline design and validate improvements after applying eco-design principles.

Core focus areas include the following:

- *Material selection*: Minimizes high-carbon materials by assessing CO_2-equivalent emissions during production.
- *Material compliance*: Ensures adherence to material regulations and avoids toxic, hazardous and concerning substances.
- *Resource optimization*: Reduces material consumption without compromising functionality.
- *Energy efficiency*: The use phase is one of the most critical areas for energy-related products. Design strategies aim to minimize energy losses by selecting materials and configurations that offer optimal electrical and thermal performance.
- *Extended lifetime*: Applies systematic methodologies to prevent product damage and extend operational life through the selection of durable materials.
- *Design for disassembly and end-of-life*: Facilitates recyclability and ease of disassembly.
- *Packaging*: Optimizes sustainable content in packaging design.

The framework also addresses trade-offs inherent in sustainable design through predefined resolution criteria. The systematic integration of these considerations enables the guidelines to support informed decision making based on quantifiable environmental metrics.

2.2 Methodological framework

The methodological approach proposed in this study is grounded in established DfS principles and is structured as a systematic, iterative framework aimed at supporting industrial decision making. The framework is designed to translate environmental assessment results—particularly from LCA—into prioritized and actionable redesign options that are compatible with real-world engineering constraints. Economics are introduced early as boundary conditions (hard/soft), while detailed cost modelling is reserved for shortlisted concepts to balance industrial constraints with innovation capacity.

As illustrated in Fig. 1, the methodology consists of nine sequential but interrelated steps. While presented linearly for clarity, the framework operates as a continuous improvement cycle that enables iterative refinement across product generations.

More specifically, the framework includes three main feedback loops. First, the baseline modelling and hotspot refinement steps (Steps 3–4) can lead to a refinement of the initial design need and boundary conditions defined in Step 2. Second, the screening of redesign options (Step 6) can trigger a return to Step 5 when concepts reveal limited GWP benefits or new improvement opportunities. Third, technical and economic validation (Steps 7–8) can redirect concepts back to ideation or requirement refinement when implementation constraints emerge. Step 9 closes the cycle by documenting implemented and deferred solutions, thereby updating the knowledge base and the baseline for future iterations.

2.2.1 Step 1: product selection

The process initiates with strategic product selection through a structured evaluation combining quantitative portfolio analysis and qualitative stakeholder input. Portfolio analysis examines the company's product range considering multiple criteria: current production volumes, market positioning, anticipated life cycle stage, and preliminary environmental significance based on available data (e.g., material intensity, energy consumption during use phase, or known end-of-life challenges, existing environmental product declarations [EPDs] or partial LCA studies when available) [18].

This quantitative screening is complemented by direct consultation with Product Management and R&D functionaries, who provide essential insights into market dynamics, emerging customer requirements, competitive pressures, and planned product evolution timelines. Products approaching scheduled redesign cycles represent particularly valuable opportunities, as sustainability improvements can be integrated without requiring dedicated development investments. Similarly, products facing regulatory pressures (e.g., upcoming restrictions on hazardous substances, energy efficiency mandates, or extended producer responsibility schemes) are prioritized.

The selection process also considers strategic alignment with corporate sustainability commitments, such as Science-Based Targets or specific EPDs required by key customers. The outcome of this step is a justified selection of one or more products that offer significant potential for environmental improvement within realistic industrial constraints.

When relevant supplier geography is variable across product families, an additional screening input can be the carbon intensity of the main sourcing regions (e.g., grid mix), to

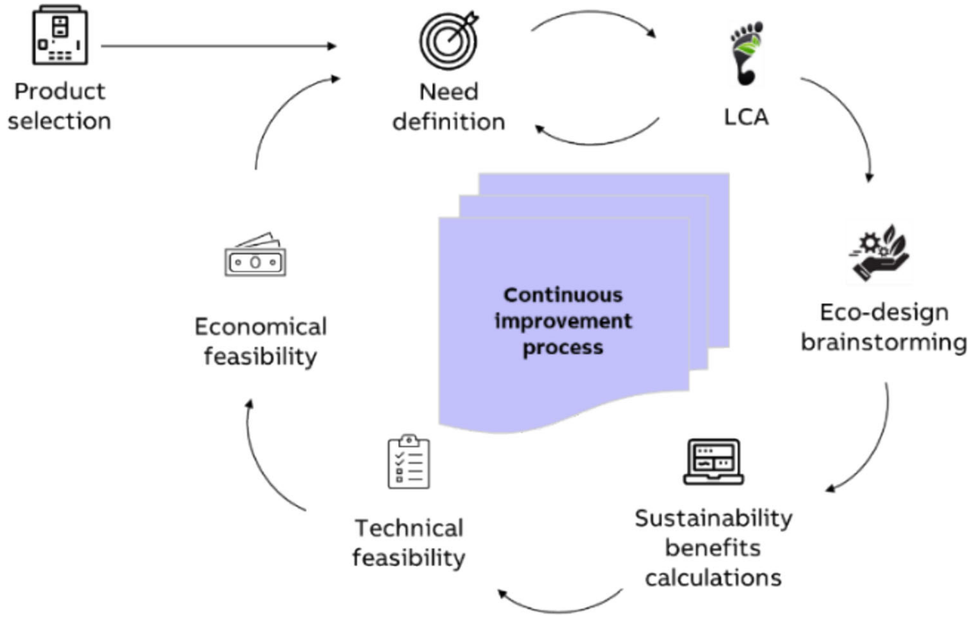


Fig. 1 Methodological framework

avoid selecting a benchmark whose upstream footprint is dominated by location-specific factors.

When no complete LCA is available for a given product, its preliminary environmental significance is estimated through simplified or prospective assessments, drawing on analogies with functionally similar products, scaling rules across product families, and published data for comparable applications. This enables an evidence-based prioritization even in the early development stages, thereby ensuring that product selection is guided by comparative environmental relevance rather than by intuition or purely commercial considerations.

2.2.2 Step 2: need definition

Following product selection, the specific sustainability objective is explicitly defined through structured dialog with relevant stakeholders. This step translates broad corporate sustainability goals into concrete, measurable targets that are applicable to the selected product. The need definition may focus on a single environmental priority or address multiple objectives simultaneously.

Common focus areas include: (i) carbon footprint reduction, typically quantified through Global Warming Potential (GWP) expressed in kg CO_2-eq, with specific reduction targets (e.g., 20% reduction compared to current baseline); (ii) enhanced circularity, measured through indicators such as end-of-life recyclability rate, recycled content percentage, or material circularity index; (iii) reduction of specific hazardous substances beyond regulatory compliance; and (iv) improvement in resource efficiency metrics, such as material-to-function ratio or dematerialization indices.

The need definition also establishes boundary conditions and constraints that guide subsequent analysis. These may include maintaining or improving current product performance specifications, respecting cost targets or acceptable cost increase thresholds, ensuring compatibility with existing manufacturing infrastructure, or meeting specific customer requirements that cannot be compromised. Crucially, this step documents the rationale behind the chosen priorities, thereby creating traceability between corporate strategy, market requirements, and the specific improvement targets that will drive the redesign process. Economic boundary conditions (e.g., target cost, CAPEX/OPEX constraints, ROI/payback expectations, and procurement constraints) are defined upfront to frame the solution space.

In industrial settings, economic considerations typically frame the design space from the outset. In Step 2, we therefore define economic boundary conditions alongside functional and sustainability requirements. To avoid suppressing innovation, we distinguish between hard constraints (non-negotiable limits such as compliance, safety, manufacturing capability, procurement restrictions, and maximum allowable cost increase where applicable) and soft constraints (innovation-friendly targets such as target cost, target payback/ROI, or cost-down expectations). Soft constraints guide ideation and prioritization without automatically excluding high-potential concepts at an early stage.

2.2.3 Step 3: LCA baseline

The environmental baseline is established through comprehensive LCA following ISO 14040/14044 standards [19, 20]. This step quantifies the current environmental performance of the selected product across its entire life cycle, from raw material extraction through manufacturing, distribution, use phase, and end-of-life treatment.

When existing LCA studies are available, they undergo critical review to verify (i) consistency with current product specifications and bill of materials; (ii) appropriateness of system boundaries and functional unit definition; (iii) currency of background data sources (e.g., Ecoinvent [21], or industry-specific databases); and (iv) alignment with the defined need from Step 2 in terms of impact categories assessed. If the existing study meets quality criteria, it is utilized directly; otherwise, it is updated or replaced.

For products lacking LCA documentation, a new study is conducted. The functional unit is carefully defined to enable meaningful comparisons with alternative designs. System boundaries are established that consider all significant life cycle stages, with particular attention paid to stages anticipated to contribute substantially to overall impacts. Primary data are collected for foreground processes (manufacturing operations under company control), while background data from established databases represent upstream supply chain processes and downstream scenarios.

For products in early development stages, where detailed specifications remain unavailable, prospective LCA is employed. This forward-looking approach constructs environmental profiles based on (i) analogies with functionally similar products already on the market; (ii) scaling relationships derived from existing product families (e.g., environmental impacts as a function of rated current or power); (iii) literature data from comparable applications; and (iv) preliminary design specifications and anticipated material compositions. While prospective LCA introduces greater uncertainty than conventional assessment [22], it provides directional guidance sufficient for identifying major impact contributors and informing early design decisions when the intervention potential is highest.

The baseline assessment can generates a comprehensive environmental profile across a single or multiple impact categories (typically including, at a minimum, climate change, resource depletion, acidification, eutrophication, and water use categories). The results are analyzed both in absolute terms and through contribution analysis to identify which life cycle stages, components, materials, or processes contribute most significantly to each impact category. This hotspot identification forms the foundation for subsequent improvement efforts.

When upstream hotspots are sensitive to supplier geography or electricity mix, these parameters are modelled as scenario assumptions within the baseline and hotspot refinement steps.

2.2.4 Step 4: need refinement based on hotspot analysis

Interpretation of LCA results frequently reveals discrepancies between initial assumptions and actual environmental performance patterns. Hotspot analysis may demonstrate that initially prioritized impact categories contribute less significantly to the overall environmental burden than anticipated, while other categories emerge as unexpectedly critical.

For example, an initial focus on reducing product weight (motivated by material cost considerations) may prove less environmentally significant than addressing energy consumption during the use phase, or vice versa. Similarly, components representing minor cost fractions may emerge as major contributors to specific impact categories due to material properties, manufacturing energy intensity, or supply chain transportation distances.

This refinement step involves a structured review of baseline results with the stakeholder group from Step 2 and explicitly compares the initial need definition against empirical evidence obtained from the environmental assessment. The need may be refined in the following ways: (i) reprioritizing impact categories based on their actual magnitude and improvement potential; (ii) narrowing the focus to specific life cycle stages or components identified as hotspots; (iii) adjusting quantitative targets based on realistic improvement potential revealed by the baseline; and (iv) expanding the scope to address additional impact categories found to be significant.

The refinement process is documented to create an audit trail that explains how the initial objectives evolved in response to evidence. This iterative approach ensures that subsequent redesign efforts concentrate resources where the environmental benefits are greatest.

The structured review with stakeholders follows a simple checklist to support transparent decision-making. First, the impact categories and life cycle stages are ranked according to their relative contribution to total impact (e.g., percentage contribution) and to the improvement potential indicated by sensitivity or scenario analysis. Second, the technical feasibility and design freedom of the main hotspots are assessed by R&D, product management, and manufacturing experts. Third, stakeholders estimate the order of magnitude of achievable improvements and verify alignment with corporate sustainability commitments and product roadmaps. Reprioritizing the impact categories is recommended when a category shows limited contribution or low technical leverage, whereas the focus is narrowed when only a few life cycle stages or components dominate the impacts and offer concrete redesign opportunities. These decisions and their rationale are documented to ensure traceability of the refined sustainability need.

2.2.5 Step 5: eco-design brainstorming

With impact priorities clearly delineated and empirically justified, structured ideation sessions are convened to generate redesign alternatives. These workshops employ a multidisciplinary approach, recognizing that effective eco-design requires the integration of diverse expertise and perspectives.

Participant selection is deliberate and includes (i) R&D engineers with deep technical knowledge of product functionality and performance requirements; (ii) procurement specialists who understand material availability, supplier capabilities, and supply chain constraints; (iii) supply chain managers who can assess implications for logistics, packaging, and distribution; (iv) simulation engineers capable of evaluating structural, thermal, or electrical performance of proposed alternatives; (v) product specialists with field experience regarding customer usage patterns, failure modes, and service requirements; and (vi) sustainability professionals who provide expertise in LCA methodology, eco-design principles, and regulatory frameworks.

Sessions are facilitated using structured creativity techniques adapted from established innovation methodologies (e.g., TRIZ, biomimicry[23, 24]) but specifically oriented toward environmental improvement. The facilitator guides systematic analysis of the product using the multiple lenses available in the DfS approach. The ideation process explicitly draws upon established eco-design guidelines based on international standards (ISO 14006 [25] for integrating eco-design into environmental management systems, IEC 62430 [26] for environmentally conscious design) and regulatory frameworks (e.g., ESPR [27], RoHS/REACH restrictions[28]).

In addition to component-level solutions, the workshop explicitly considers supply-chain levers (supplier alternatives or regionalization options) when hotspots are upstream-dominated, treating supplier/region scenarios as design variables to be tested in the screening step.

Critically, evaluation is deliberately deferred during the initial ideation phases. Participants are encouraged to propose alternatives without immediate judgment regarding feasibility or cost, thereby fostering creative exploration beyond incremental improvements. Design engineers with expertise in the existing CAD models play a particularly important role, as they can use their technical knowledge to challenge assumptions embedded in current configurations and identify design degrees of freedom that may not be apparent to other participants.

Concept generation is organized into two complementary streams: (i) no-regret concepts, expected to be compatible with current economic boundaries, and (ii) ambitious concepts, which intentionally explore higher sustainability gains and may require iteration (e.g., alternative processes, learning effects, supplier strategies) to meet economic targets.

All proposals are documented systematically to capture the specific design modification, as well as the environmental rationale, anticipated benefits, and preliminary concerns or uncertainties. Typical workshop outputs range from 20 to 50 distinct concepts, which vary in scope from minor material substitutions to fundamental architectural redesigns.

2.2.6 Step 6: sustainability benefits calculations

Proposals generated through collaborative workshops undergo rapid environmental screening to quantify potential benefits and prioritize concepts for detailed evaluation. This assessment employs LCA software (e.g., SimaPro) and eco-design tools capable of processing bill-of-materials data or reading CAD files directly.

For each concept, a modified LCA model is constructed by adjusting the baseline model (from Step 3) to reflect proposed changes. Modifications could include (i) material substitutions, with updates of material types and quantities; (ii) manufacturing process changes that adjust energy consumption, waste generation, or auxiliary material requirements; (iii) use phase modifications that revise energy consumption profiles or maintenance requirements; and (iv) end-of-life scenario adjustments that update recycling rates, recovery efficiencies, or disposal pathways.

Given the large number of concepts and the preliminary nature of specifications, this screening employs simplified modeling approaches that prioritize speed over precision. Uncertainty is acknowledged and managed through sensitivity analysis for critical parameters. The results are expressed as percentage changes relative to the baseline values across the key impact categories identified in Step 4, as this ensures comparability across concepts despite differences in modeling resolution.

The concepts used for the framework are classified based on the following environmental performance assessments: (i) clearly beneficial, showing improvement across all or most relevant impact categories; (ii) trade-off scenarios, improving some categories while worsening others; (iii) negligible impact, showing minimal change; and (iv) clearly detrimental, worsening environmental performance. This classification enables prioritization, so subsequent detailed evaluations are focused on concepts demonstrating significant improvement potential or requiring deeper analysis to resolve trade-offs.

The screening also identifies concepts in which environmental benefits are highly sensitive to specific assumptions (e.g., electricity grid mix for use-phase energy consumption, recycling infrastructure availability for end-of-life scenarios, etc.). These sensitivities inform subsequent technical evaluation and highlight parameters requiring precise specification. However, given the preliminary nature of many concepts, the use of simplified models deliberately trades precision for speed.

To address the uncertainty created by this trade-off, the present framework (i) constrains model changes to the level of detail supported by the concept description, (ii) applies sensitivity analysis on critical parameters such as material quantities and use-phase energy profiles, and (iii) interprets results in terms of performance classes rather than exact values. Concepts flagged as environmentally promising or characterized by relevant trade-offs are subsequently evaluated using more detailed LCA models as they progress through the design funnel, resulting in further progressive reductions in uncertainty.

Where upstream results are sensitive to electricity mixes, alternative grid/region assumptions are modelled as scenarios to quantify the effect of potential relocation or supplier switches. Before entering detailed technical validation, shortlisted concepts undergo a rapid order-of-magnitude economic sanity check to identify options clearly incompatible with major cost constraints.

2.2.7 Step 7: technical feasibility

Environmentally promising concepts undergo rigorous technical validation to confirm compatibility with functional requirements, manufacturing capabilities, quality standards, and regulatory compliance. This step prevents the pursuit of environmentally attractive solutions that cannot be reliably implemented within industrial constraints.

Technical assessment methods vary according to concept maturity and risk level, as follows:

- *Computational simulation*: Finite element analysis for structural integrity, computational fluid dynamics for thermal management, electromagnetic simulation for electrical performance, or tolerance analysis for assembly feasibility. Simulations enable rapid evaluation of multiple variants and identification of design parameters requiring optimization.
- *Physical prototyping*: Fabrication of representative samples or functional prototypes using proposed materials, geometries, or manufacturing processes. Prototypes undergo standardized testing protocols to verify compliance with product specifications (e.g., electrical ratings, mechanical strength, environmental resistance, safety certifications, etc.).
- *Manufacturing trials*: Pilot production runs to assess compatibility with existing equipment, identify process parameter adjustments, evaluate yield rates, and detect quality issues not apparent in laboratory-scale prototyping.
- *Supplier qualification*: For concepts requiring new materials or components, supplier capabilities are assessed through audits, sample evaluations, and capacity verification to ensure reliable supply at the required quality and volume.

Technical evaluation generates binary outcomes (feasible/not feasible) or identifies conditional feasibility requiring specific modifications or additional development. Concepts failing technical validation are documented with a clear rationale, and this allows future re-evaluation if enabling technologies or capabilities emerge. Technically validated concepts proceed to economic assessment, often with refined specifications addressing issues identified during feasibility testing.

2.2.8 Step 8: economical feasibility

Economic assessment is conducted exclusively for concepts that successfully pass both environmental and technical validation. This deliberate sequencing prevents the premature elimination of potentially valuable solutions based on cost considerations alone while ensuring that economic resources are invested only in analyzing viable alternatives.

Economic evaluation encompasses the following multiple dimensions:

- *Direct cost analysis*: Comparison of material costs, manufacturing costs (including labor, energy, tooling, and equipment), and quality assurance costs between baseline and proposed designs. Cost models account for volume effects, learning curves, and supplier pricing structures.
- *Life cycle cost assessment*: Evaluation of costs across the entire product life cycle, including manufacturing as well as distribution, installation, operation (particularly energy costs for products with significant use-phase consumption), maintenance, and end-of-life treatment. This perspective may reveal that concepts with higher initial costs deliver net savings over the product lifetime.
- *Investment requirements*: Quantification of one-time investments required for implementation, such as tooling modifications, equipment purchases, facility adaptations, or certification testing. Investment costs are amortized over anticipated production volumes to determine per-unit impact.
- *Risk-adjusted valuation*: Assessment of economic uncertainties, including material price volatility, exchange rate fluctuations, regulatory compliance costs, or potential warranty implications. Sensitivity analysis identifies concepts whose economic viability depends critically on specific assumptions.
- *Strategic value considerations*: Qualitative evaluation of benefits not easily monetized, such as enhanced brand

reputation, competitive differentiation, access to environmentally conscious market segments, or reduced exposure to future regulatory restrictions.

The results are synthesized into decision-support formats that enable comparisons of concepts across environmental performance, technical risk, and economic implications. Multicriteria decision analysis frameworks may be employed to identify optimal solutions or acceptable trade-off ranges.

Importantly, economic evaluation does not automatically eliminate concepts with unfavorable cost profiles. Instead, the results inform strategic decisions regarding acceptable investment levels for environmental improvement, potential pricing adjustments, or phased implementation strategies that defer costs until economies of scale improve viability.

Economic considerations are deliberately excluded during the initial ideation phase to avoid prematurely discarding environmentally ambitious concepts and to maximize creative exploration. However, economic feasibility is systematically reintroduced after environmental and technical validation. Only solutions that satisfy both environmental and economic criteria are shortlisted for implementation, thereby mitigating the risk of generating environmentally attractive but economically unfeasible designs. Step 8 performs detailed economic feasibility only on shortlisted concepts that have passed prior screening and validation steps, ensuring analytical effort is proportional while maintaining early-stage openness to innovative alternatives.

2.2.9 Step 9: documentation and continuous improvement

The methodology operates as a continuous improvement cycle, with systematic documentation ensuring that the knowledge generated during each iteration informs future efforts. All concepts generated during brainstorming, regardless of implementation status, are captured in a structured database.

As illustrated in Fig. 1, the cycle concludes by feeding insights back to the starting point. Implemented improvements update the baseline for subsequent iterations, while deferred concepts populate a pipeline of potential future enhancements. This cyclical structure ensures that sustainability considerations remain embedded throughout the product's evolution across multiple generations. The framework's iterative nature also accommodates evolving corporate priorities, regulatory requirements, customer expectations, and technological capabilities. Periodic reinitiation of the cycle (e.g., annually or aligned with product refresh cycles) ensures that environmental performance continuously improves in response to both internal innovation and external developments in materials science, manufacturing technology, and sustainability best practices.

2.3 Tools and data sources

From an instrumental point of view, the LCA software SimaPro was used for modeling and conducting hotspot analyses, supplemented by commercial databases for secondary data (e.g., Ecoinvent 3.11). Integration with an ERP system enabled the extraction of bills for materials and supplier metadata and ensured consistency between the LCA inventories and actual product configurations. CAD tools were used to navigate the 3D model and processing redesign proposals. Eco-design software was also employed to enable rapid comparisons of the environmental impacts. In this context, sector-specific databases containing the technical properties of materials were particularly useful in facilitating the selection of alternatives with a lower impact, as determined by the LCA metrics.

A key feature was the direct interaction between the eco-design software and the CAD files. This was useful for automatic calculation of the bills for materials and their associated environmental contributions, including assembly processes, where available.

3 Design for sustainability applied to a real case

3.1 Case study: medium-voltage circuit breaker in the context of design for sustainability

3.1.1 Product selection through portfolio analysis

ABB Group is a Swiss-Swedish multinational corporation based in Switzerland. ABB is situated in more than 100 countries, and it has 105,000 employees around the world. The group is composed of 3 different business areas: Electrification, Motion, and Process Automations. Throughout its history, ABB has developed innovative solutions in all its divisions. The ABB Electrification business area has a wide range of products for medium-to-low voltage applications, including EV infrastructure, solar inverters, modular substations, distribution automation, power protection, wiring accessories, circuit breakers, enclosures, cabling, sensing, and control.

For the case study, our analysis focused on a medium-voltage circuit breaker. A representative circuit breaker was identified by performing a portfolio analysis of production data spanning one year of production from the ABB Dalmine plant. Data were extracted from the ERP system to ensure data reliability. This top-down analysis identified the most frequently produced device within the equipment division, following ABB's make-to-order production model, which minimizes inventory in accordance with lean manufacturing principles.

Table 1 General characteristics of the VD4 series

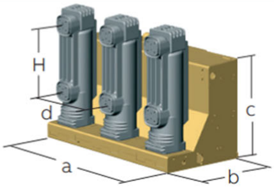
Rated voltage (1)	**kV**	**17.5**		
Rated frequency	Hz	50 - 60		
Rated thermal current	A	630 . . . 4000 (2)		
Short-time withstand current and breaking capacity	kA	16 ... 31.5	40 ... 50	63
Making capacity	kA	40 ... 80	100 ... 125	164
Admissible short-time withstand current	s	3	3	3 (8)
Fixed / withdrawable version		•/•	•/•	•/•
Maximum overall dimensions (fixed version)  	d (mm)	150 - 275	150 - 210 - 275	275
	H (mm)	205 - 310	310	310
	a (mm)	450 - 700	450 - 570 - 700	750
	b (mm)	424	424	459
	c (mm)	461 - 599 (5)	599 (5) (7)	677
Weight	kg	73 - 105	94 - 180	260
Embedded poles		•	•	-
Assembled poles		-	-	•

Fig. 2 Medium-voltage circuit breaker

The VD4 circuit breaker (Fig. 2 and Table 1) emerged as the most prevalent item in the primary production line, owing to its two decades of market presence and established position as a benchmark within the vacuum switch sector. Its reliability and adaptability across various ratings have made it a standard choice for utilities and heavy industries, including steelworks, cement factories, and refineries.

This device is designed to control the flow of electrical current, enabling its interruption or reconnection at any given moment. The key component of the circuit breaker is the electrical contact, which is housed within a pressure vessel filled with compressed dry air. This design approach was implemented to minimize the occurrence of electrical discharges during switching operations. The insulating effect is achieved by compressed air, which serves as a dielectric medium in this application. The circuit breaker comprises numerous components made from various materials, each contributing significantly to the overall environmental impact of the product [13, 29].

3.1.2 Purpose of the analysis

In this study, the focus was on GWP, an environmental impact category expressed in kilograms of CO_2 equivalents (kg CO_2eq). This unit quantifies the total greenhouse gas emissions throughout the product's life cycle by converting various greenhouse gases into CO_2 emissions, using CO_2's GWP as the reference.

The conversion relies on emission factors derived from mathematical models that quantify the radiative forcing potential of different greenhouse gas molecules relative to CO_2. For instance, methane (CH_4) has an emission factor of 29.8 kg CO_2eq/kg CH_4, indicating that the emission of 1 kg of CH_4 is equivalent to 29.8 kg of CO_2 in terms of global warming impact. The emission factors used in this analysis are based on the most recent assessment reports provided by the Intergovernmental Panel on Climate Change (IPCC), a scientific institution established by the United Nations. The IPCC reports serve as the international scientific reference for climate policies and LCA studies. The decision to prioritize GWP over other environmental impact categories was not arbitrary but strategically driven by market intelligence and stakeholder requirements. Following consultations with product managers and systematic analysis of customer requests and tender specifications, GWP emerged as the primary environmental concern across key market segments.

The focus on GWP represents a pragmatic response to current market demands. However, the methodology is designed to accommodate multicriteria environmental assessment in subsequent phases. This phased approach balances immediate applicability with methodological extensibility, so it maintains transparency regarding scope and limitations while providing a foundation for comprehensive life cycle impact assessment.

As part of the analysis, several targets were defined:

- Reducing CO_2 eq. upstream emissions: The first objective was to determine the reduction of CO_2 emissions related to the manufacturing process, referred to as the "upstream," which includes the total amount of CO_2 eq. generated during the production of the circuit breaker. This emission can be divided into two main components:
    - CO_2 eq. emissions from raw materials; this includes emissions generated during the production of raw materials used to manufacture the circuit breaker.
    - CO_2 eq. emissions from the circuit breaker manufacturing process; this includes emissions resulting from energy consumption during manufacturing of the circuit breaker.
- Reducing CO_2 eq. use phase emissions: Another type of CO_2 eq. emissions targeted for reduction is associated with the circuit breaker's use phase and results from energy losses occurring throughout the entire service life of the product. These losses are directly linked to the device's energy efficiency and the processes taking place inside the circuit breaker. Every instance of energy loss effectively increases CO_2 eq. emissions during the use phase, since the lost energy was previously generated and its production involved carbon emissions. Consequently, any inefficiency in energy performance increases the carbon footprint attributed to the generated energy.
- Increasing recyclability: This target of the analysis was to prioritize the use of recyclable materials and select raw materials with the highest possible recovery rates. This strategy aims to mitigate the risk that the components of a product, upon completion of the product's lifecycle, cannot be effectively recycled and consequently end up in landfills or are relegated to low-value applications, such as fillers in construction.
- Improving disassembly: The analysis also considered the product's disassembly. The circuit breaker must be designed to allow its easy separation into individual components to enable their transfer to appropriate recycling processes. Facilitating straightforward disassembly supports efficient material recovery, reduces disposal costs, and enhances compliance with circular economy principles.

3.1.3 Input data

Before starting the analysis and brainstorming sessions, all necessary input data were collected, with special attention to the critical factors of detail and quality. The input data included 3D models that can be opened in dedicated software, as well as manufacturing and assembly drawings containing information on production processes, protective coatings, assembly sequence, welding methods, and other key parameters. The input data also includes the Bill of Materials (BOM), which lists all components and the materials used in their fabrication.

A hotspot analysis utilizing the LCA methodology was performed on the circuit breaker studied to determine areas for environmental impact reduction. The LCA was conducted using SimaPro software with the commercial Ecoinvent 3.11 database. The Life Cycle Inventory was constructed using both primary and secondary data. The product studied is an automatically operated electrical device that is used to control and protect an electrical circuit from damage caused by overload or short circuit. The functional unit manages and protects the electrical continuity of the circuit to which it is applied, at a use rate of 30% and a load factor of 50% during a service life of 20 years in Europe. The reference flow is an average, single, withdrawable VD4 p.150 with a PT1 pole device with 1250A nominal current, including related accessories and packaging.

Note that the reference service life of 20 years is a theoretical period selected for calculation purposes only and is not representative of the minimum, average, or actual service life of the product. This LCA is a "cradle-to-grave" analysis. The 30% use rate and 50% load factor were defined in consultation with product managers and field experts as conservative standardized assumptions for comparative LCA purposes and were considered to reflect typical duty profiles in key applications (utilities and heavy industry). These were not intended to predict any specific installation, but to ensure a consistent reference scenario across alternative design options.

Specifically, the system boundaries are structured according to three main phases:

a)*Upstream manufacturing stage*, which encompasses all activities preceding ABB's direct manufacturing operations. This includes raw material extraction and processing, the production of semi-finished parts, components, and subassemblies by both direct (tier-1) and indirect (tier-2 and beyond) suppliers, and transportation of these materials and components to ABB manufacturing facilities. The upstream stage captures the embodied environmental impacts of all purchased inputs entering ABB's production system.

b)*Core manufacturing stage,* which encompasses activities under direct ABB operational control at manufacturing sites. This includes utility consumption (electricity, natural gas, water, and compressed air), waste generation and treatment from production processes, production and use of packaging materials, and all process-specific emissions associated with assembly, testing, and quality assurance operations. The core stage represents the environmental impacts directly attributable to ABB's manufacturing activities.

c)*Downstream stages,* which encompass the following life cycle phases subsequent to product dispatch from ABB manufacturing facilities:

- *Distribution stage:* Transportation of the final product from ABB facilities to the site of installation
- *Installation stage*: Activities related to product installation at the customer site, including end-of-life treatment of packaging materials once the product is unpacked and commissioned
- *Use stage*: Energy consumption during product operation and maintenance throughout the reference service life of the product
- *End-of-life stage*: All activities related to decommissioning, disassembly, waste treatment, material recovery, recycling, and final disposal of the product at the end of its service life

Exclusions from the system boundary, according to Standard EN50693 [15], include capital goods, such as machinery, tools, buildings, infrastructure, packaging for internal transports, and administrative activities, which cannot be allocated directly to the production of the reference product.

Scraps for metal working and plastic processes are also included when already defined in Ecoinvent. Furthermore, the product was broken down into components and subassemblies to highlight priority areas for improvement.

The upstream phase, primarily the supply of raw materials, accounts for approximately 50% of the total environmental impact. The constituent materials analysis (Fig. 4) revealed that steel accounts for 69.6% of the switch's weight. Aluminum and copper are also widely used, mainly in poles. In contrast, the core manufacturing phase demonstrated ABB's efficiency in its production processes. The distribution, installation, and end-of-life phases had minor impacts. The use and maintenance phases accounted for 48% of the product's lifecycle impacts, highlighting the significant contribution of the operational power losses. The circuit breaker's resistance is the main variable that influences the use phase. A higher resistance means greater dissipation; therefore, the CO_2 equivalent emissions are greater. Analysis of the upstream phase allowed us to identify the components with the greatest environmental impact, thereby providing a basis for prioritizing improvements.

One of the key input elements was the LCA tree, reported partially in Fig. 3. This tool enables an analysis of the flow of CO_2 eq. emissions for the product and clearly highlights the components or assemblies that make the highest contribution.

The LCA tree also allows for a comparison between emissions generated during the use phase and those produced during manufacturing. In this case study, the emissions from production were roughly comparable to those occurring during the operational phase of the product. This insight was crucial in shaping the next steps of the design process.

Figure 3 presents the LCA results tree, showing that approximately 51% of total GWP is associated with upstream and core manufacturing stages, 49% with the use phase (including maintenance), and around 2% with distribution, installation, and end-of-life. This near balance between manufacturing and use impacts was crucial in guiding the subsequent DfS activities, as it justified targeting both the upstream material/process improvements and use-phase loss reduction.

3.1.4 Brainstorm sessions and final report

After collecting all the necessary input data, a series of brainstorming sessions was organized. Participants from different areas and holding various roles within the organization were invited to join. This diversity proved highly valuable as it often led to creative and practical solutions that might not have emerged in more uniform groups.

To stimulate creativity, participants were encouraged to temporarily "forget" about constraints, which aided them in thinking outside the box. During the sessions, cost-related aspects were deliberately omitted to avoid limiting the idea-generation process. The brainstorming was carried out in a systematic manner by analyzing individual components and assemblies step by step. The moderator was responsible for asking key questions and inspiring participants to explore new solutions.

The brainstorming sessions resulted in 42 ideas (Table 3). Each concept was documented in the report on a separate page. For ideas requiring changes in geometry, shape, or assembly type, corresponding 3D models were prepared. To evaluate the proposals, the function of the analyzed components was first assessed. Once the function was maintained for the alternative solutions, specialized LCA and eco-design

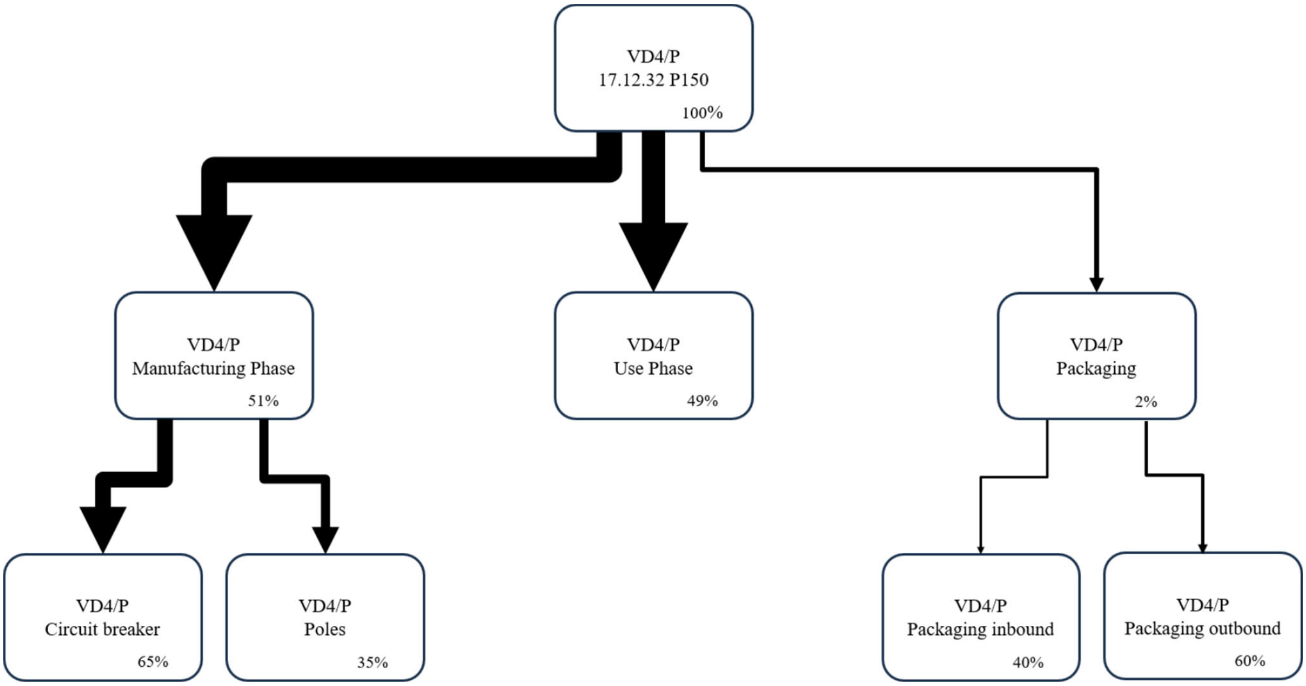


Fig. 3 LCA results tree

software was used to calculate their carbon footprints. The baseline design was then compared with the suggested solutions to estimate the potential reduction in CO_2 eq. emissions.

As each component had multiple environmentally conscious design solutions, the next step was to prioritize the ideas. Each idea was evaluated in terms of the ease of technical implementation and the potential to reduce environmental impact. The most promising ideas, according to these criteria, were then integrated into a single, coherent concept design.

For the standard linkage, the alternative concept was shortlisted because it preserved the original function while reducing material demand and eliminating machining operations. During consolidation, alternative solutions addressing the same function were compared using an explicit tie-breaking set: feasibility under existing forming/tooling constraints, expected robustness (stiffness/load-bearing), and implementation risk. The selected option was retained conditionally, with the next validation stage planned as FEM stress analysis to confirm load resistance, ensuring that the CO_2-eq benefit does not compromise functional requirements.

For the housing, the recycled ABS option was consolidated due to its high CO_2-eq reduction potential; however, it was treated as conditional to qualification and requirement compliance. Specifically, the material substitution is accepted only if the recycled grade meets mechanical properties, surface finish, strength, and other technical parameters stated for the component. This rationale is now reported explicitly in the decision matrix to clarify why high-benefit options may still require additional technical validation before final adoption.

To improve replicability, the consolidation of ideas into the final concept was supported by a concise decision matrix. Each idea was scored on: (i) expected GWP reduction from Step 6 screening; (ii) implementation feasibility/technical risk (anticipated effort for Step 7 validation); and (iii) compatibility with existing manufacturing/tooling and supply constraints. When multiple ideas addressed the same function, a tie-break rule was applied prioritizing solutions with higher robustness expectations and lower implementation risk; solutions requiring further evidence were retained as ‘conditional’ pending FEM/material qualification. Table 2 summarizes the concise decision matrix used to prioritize and consolidate shortlisted ideas. The matrix combines the expected GWP reduction from Step 6 screening with implementation feasibility and compatibility with existing manufacturing, tooling, and supply constraints, thereby making the concept consolidation process more transparent and replicable. (GWP score: $1 = <20\%$ reduction; $2 = 20–50\%$ reduction; $3 = >50\%$ reduction.

Technical feasibility/implementation risk: 1 = low; 2 = medium; 3 = high.

Compatibility with manufacturing/tooling/supply constraints: 1 = high compatibility; 2 = moderate adjustments required; 3 = major changes required.)

Ideas with high GWP reduction and no critical feasibility or compatibility score were consolidated directly, whereas

Table 2 Decision matrix used to prioritize and consolidate shortlisted ideas

Idea category	Target component/function	Proposed redesign option	Screening CO_2-eq reduction	GWP score	Technical feasibility/implementation risk	Compatibility with manufacturing/tooling/supply constraints	Decision	Rationale/validation need
Material minimization	Standard linkage	Replace solid square bar with bent sheet metal components	− 40.8%	2	2	2	Selected (conditional)	Preserves function while reducing material use and machining operations; requires FEM validation of stiffness/load-bearing performance
Alternative materials	Housing	Replace virgin ABS with closed-loop recycled ABS	− 85.7%	3	2	2	Selected (conditional)	Very high CO_2-eq reduction potential; retained only if recycled grade meets mechanical, surface-finish, and strength requirements
Process change	Custom-made screw	Replace current process with forging	− 50.0%	2	2	2	Shortlisted (conditional)	Promising due to scrap reduction and lower screening footprint; requires supplier/process feasibility verification
Assembly/joining redesign	Crossbar assembly	Eliminate lower plate welding; use hemming + riveting with thinner pre-galvanized sheet	− 31.7%	2	2	2	Shortlisted (conditional)	Reduces material and joining burden; requires validation of structural rigidity and assembly robustness
Part reduction/process integration	Sleeve assembly	Replace welded multi-part solution with one-piece forging/forming concept	− 57.7%	3	3	3	Deferred/conditional	Strong reduction potential, but higher implementation effort and tooling/manufacturing changes require additional validation before consolidation

options with strong environmental potential but higher uncertainty were retained as conditional or deferred pending targeted validation.

Subsequent recalculation of the CO_2 eq. emissions exclusively for the manufacturing phase (the so-called upstream) revealed that the potential reduction could be as much as 27%. This assumption was a direct consequence of the hotspot analysis, in which the manufacturing phase emerged as one of the two most impactful phases. The "up to 27%" reduction refers to the consolidated concept in which a coherent subset of the most promising ideas (in terms of environmental benefit and technical feasibility) was combined, rather than considering the hypothetical simultaneous implementation of all 42 initial ideas.

However, note that implementing all proposed ideas is challenging, as other conditions, particularly those related to implementation costs, must also be met.

The 42 ideas were first grouped into 23 categories using an affinity-based clustering, where concepts sharing a common functional target (e.g., material minimization of structural parts, alternative materials for housings, process changes for joining, improved disassembly features) were aggregated (Table 3). This categorization facilitated subsequent screening by enabling the team to compare options that addressed similar functions or components. This affinity-based clustering is conceptually aligned with Mayring-style qualitative content analysis and with applications in industrial contexts, such as those described by Castiblanco et al. [30], where functionally similar improvement tools are consolidated into a smaller number of categories to support prioritization.

Table 3 All ideas

Idea	
#1 Structure:	#22 Frame:
Change material, no welding	Change material
#2 Structure:	#23 Shaft:
3 mm, pregalvanized, no welding	Change from full rod to tube
#3 Structure:	#24 Shaft:
Eliminate unnecessary components	Reduce diameter
#4 Structure:	#25 Shaft:
Green steel	Change welding
#5 Structure:	#26 Shaft:
Change location	Reduce zinc coating
#6 Support:	#27 Shaft:
Process change	Forging
#7 Connecting rod:	#28 Bush:
Different design	Change material
#8 Connecting rod:	#29 connecting rod:
Reduce screw diameter	Forging
#9 Connecting rod:	#30 Bushing mounting:
Change manufacturing process	Reduce silver plating
#10 Connecting rod:	#31 Bushing mounting:
Replace the manufacturing process	Simplify the bushing design
#11 Screw:	#32 Bushing mounting:
Replace the manufacturing process	Reduce diameter
#12 Truck:	#33 Bushing mounting:
DX51 change	Die casting
#13 Truck:	#34 Bushing mounting:
Riveting, reduce sheet metal and zinced steel	Simplify the design
#14 Structure:	#35 Pole's contact and bushing:
Eliminate welded nuts	Merge into one part
#15 Crossbeam:	#36 Poles:
Remove the support, change the material	Change material to PT
#16 Crossbeam:	#37 Brass components:
Change material	Change process
#17 Crossbeam:	#38 Brass components:
Simplify the shape handles	Solve disassembly issue
#18 Crossbeam:	#39 Panel:
Reduce parts by embossing	Snap fit
#19 Wheel:	#40 Panel:
Forging	ABS recycling
#20 Wheel:	#41 Tulip:
Die casting	Reduce fin thickness
#21 Frame:	#42 Tulip:

3.1.5 Proof-of-concept brainstorming outcomes

After the input data were collected, the brainstorming session was initiated. At the beginning, all the targets and challenges that needed to be addressed were outlined. The brainstorming was divided into several sessions, and participants from different departments were involved to encourage out-of-the-box thinking. At the beginning of the meeting, a printed guide explaining a methodological framework to be followed during the meeting was distributed to help participants generate valid outputs. This guide was based on internal directives, such as the ABB Circularity Framework and eco-design standards [2], as well as government and international regulations, including ISO 14006 [1627], ESPR regulations [14], and IEC TR 62430 [31]. During the sessions, the team analyzed the assembly part by part. They were displayed in 3D, with their function clarified and all figures aligned with the as-is situation. This included information such as the material, surface treatment, criticality of the part, manufacturing process, and supplier origin. Updating the team on all the data and characteristics of each component clarified potential

Table 3 (continued)

Idea	
#1 Structure:	#22 Frame:
Change the coating	Change fin shape

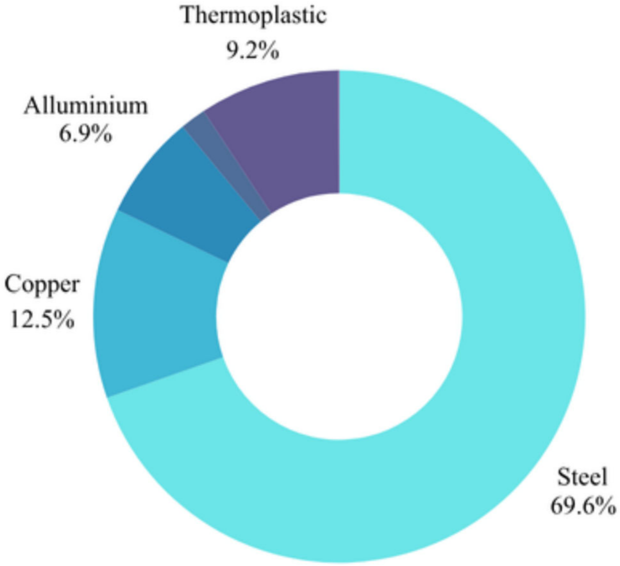


Fig. 4 Constituent materials

areas for improvement, helping everyone generate innovative ideas for reducing the carbon footprint (Fig. 4).

The brainstorming moderator posed triggering questions to guide the discussion. Participants were encouraged to set aside limitations and use their imaginations to propose radical solutions. Throughout the session, the moderator took notes on each idea proposed by the group. After the brainstorming, each idea was presented on a separate slide. For the ideas with the greatest potential, a 3D model was created for the use of dedicated software to evaluate potential environmental impact savings.

Below are selected ideas that could have a significant impact on reducing CO_2 eq. emissions. This is only a small sample from the many proposals, but it effectively illustrates the diversity of solutions that were suggested.

3.1.6 Material minimalization

For the standard linkage, originally made from a solid square bar, an alternative was proposed that used bent sheet metal components (Fig. 5). In this case, this alternative significantly reduced the amount of material required to achieve the same function. An additional advantage of this solution was the elimination of the machining operations necessary in the original design to create holes and slots. Although bending sheet metal into this type of shape may seem complex, it is in fact easily achievable with the right tooling and forming process. The next assessment stages will be to perform a stress analysis using the Finite Element Method to verify that the proposed solution can withstand the required loads. In this case, the improvement would result in a 40.8% reduction in kg CO_2 eq.

3.1.7 Exploring alternative materials

In the presented example, the original housing was made from standard ABS. An alternative was proposed using ABS sourced from a closed-loop recycling process, meaning that the raw material was recovered from waste and reused (Fig. 6). The results demonstrate the significant impact this approach can have on reducing CO_2 eq. emissions. However, the new material must still meet all remaining requirements, such as mechanical properties, surface finish quality, adequate strength, and other technical parameters. Using recycled plastic would significantly reduce the carbon footprint by 85.7% compared to the original material.

3.1.8 Exploring an alternative manufacturing process

The proposed idea concerned a custom-made screw that is not a standard market component. As part of the evaluation, an attempt was made to identify a more efficient production process (Fig. 7). The analysis showed that forging is a more favorable solution for this screw in terms of reducing CO_2 eq. emissions. Despite the need for material heating and energy consumption, this method performs better in the environmental balance. This improvement is primarily due to the significant reduction in scrap, as less scrap is produced with forging than with machining. In fact, testing the change revealed a 50% reduction in kg CO_2 eq.

3.1.9 Alternative to welding and innovative process

For the crossbar assembly shown in Fig. 8, an attempt was made to eliminate the welding process involving the lower plate. The lower plate had been introduced to support the crossbar; however, this added to the amount of material and welding required for the component. Therefore, the proposed change was to eliminate the lower plate by introducing an innovative method called Hemming bending. The aim of this method is to reinforce the component using bending, which has a lower environmental impact than the lower plate solution. To eliminate welding, riveted joints were introduced, which significantly reduces the amount of energy required during assembly (Fig. 8). Riveting is far less energy intensive than welding and therefore generates lower CO_2 eq. emissions. Additionally, the sheet thickness was reduced,

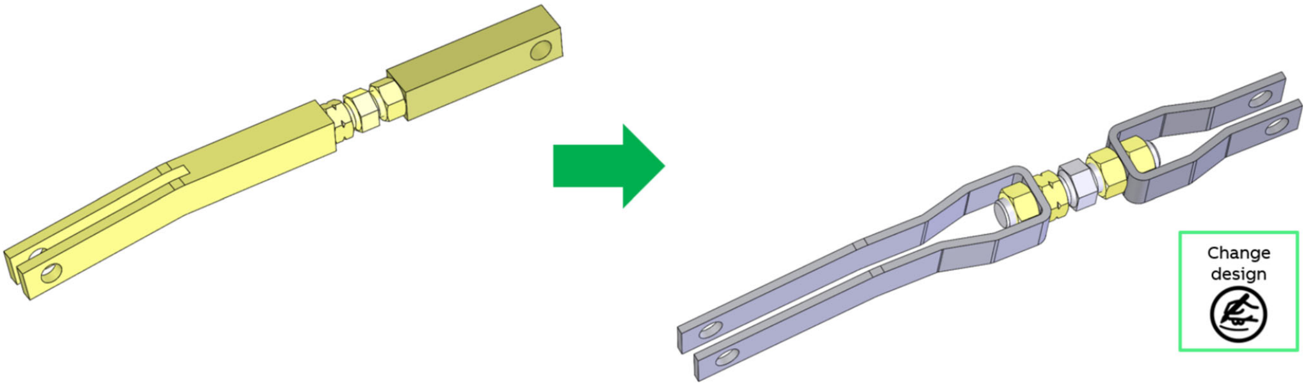


Fig. 5 Sheet metal parts instead of a milled fully filed rectangular rod

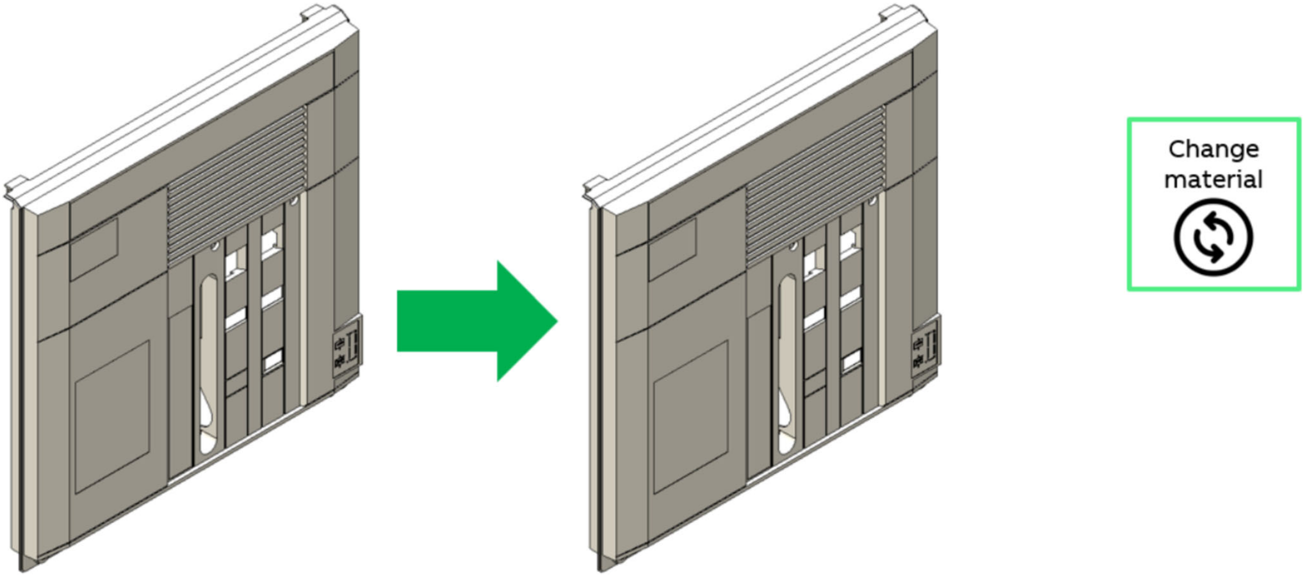


Fig. 6 Material change from new to recycled ABS

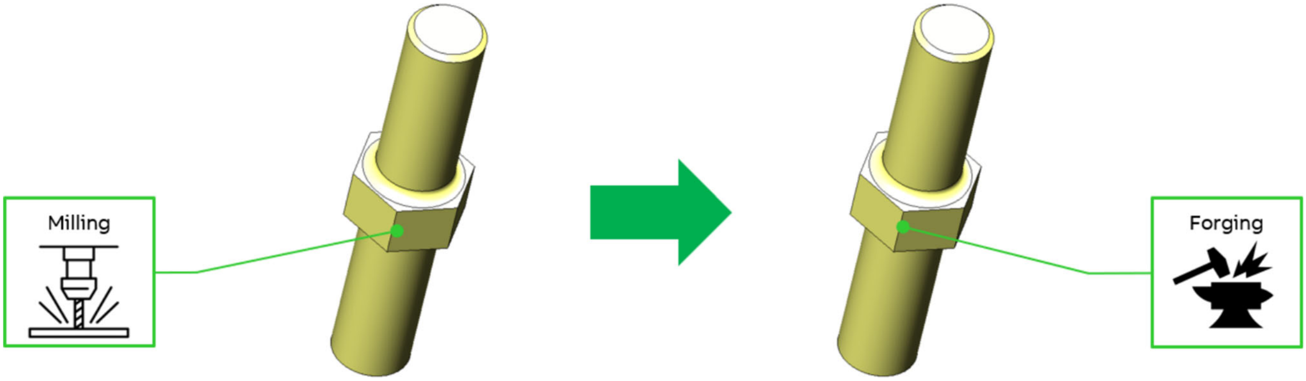


Fig. 7 Forging instead of milling

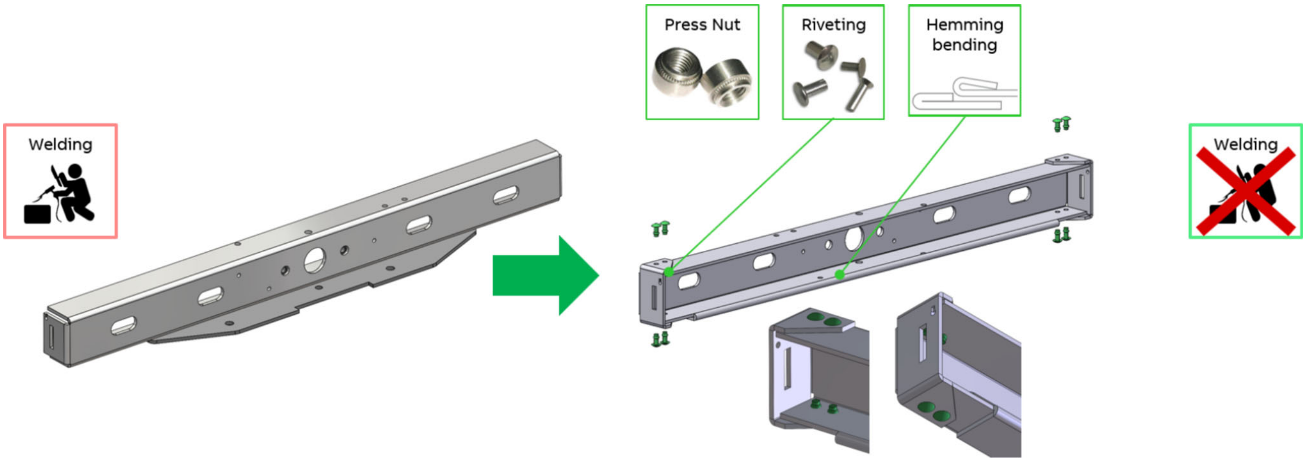


Fig. 8 Cross beam alternative design

and Hemming bending was applied to maintain the required stiffness. In the original design, the beam was painted after welding, whereas the use of galvanized sheet metal in the new solution eliminated the need for painting and further reduced environmental impacts. In this case, a reduction of 31.7% in GWP was reached.

3.1.10 Reducing part numbers

For the proposed design, an alternative concept with fewer parts was suggested. This was achieved by eliminating the welding of the sleeve (Fig. 9). In the new solution, forging and forming were used to create the component as a single piece. By removing additional parts, the entire manufacturing process associated with producing the sleeve was also eliminated, with a further positive impact on reducing CO_2 eq. emissions. As with the other components analyzed, this method had a lower GWP impact, with a reduction of 57.7%.

4 Results and discussion

Despite recent advances in systematic approaches to sustainability in industry, three key gaps remain in the state of the art: (1) lack of methodologies that translate LCA evidence into structured, prioritized design decisions that are usable by interdisciplinary industrial teams; (2) limited replicability across product families, especially in engineering-intensive sectors such as electrical distribution; and (3) insufficient integration of eco-design within existing product development frameworks, particularly in large manufacturing corporations where decisions must balance technical performance, safety, cost, compliance, and sustainability.

To address these gaps, this study proposes an innovative eco-design methodology that integrates LCA results with a structured decision-making framework applicable within industrial product-development processes. Unlike existing approaches that focus either on tools (e.g., LCA) or on high-level principles, this methodology creates a bridge between environmental evidence and actionable redesign options to enable organizations to identify hotspots, prioritize interventions, and compare alternative configurations.

The method was developed and tested within the electricity distribution sector in response to a concrete industrial need in a high-complexity environment characterized by stringent safety requirements, long asset lifetimes, and heavily engineered components. By grounding the methodology in a real industrial case, the present study has demonstrated both its practical applicability and its scalability across product families to provide a replicable approach that complements and operationalizes existing scientific frameworks.

The following steps were taken to achieve the desired result: (1) A portfolio analysis was conducted to select a representative benchmark and specify the main company need for the selected product; (2) the bill of materials was aligned with the LCA results to locate the hotspots; (3) an interdisciplinary workshop was carried out to generate redesign options based on the eco-design approach; and (4) an LCA comparison was made between alternative configurations to quantify environmental performance. The entire process was designed as a continuous improvement and promoted knowledge transfer between product lines.

To reflect industrial practice, economic constraints are considered from the outset as boundary conditions; however, detailed cost modelling is intentionally postponed to the shortlist stage to avoid disproportionate effort on early-stage alternatives.

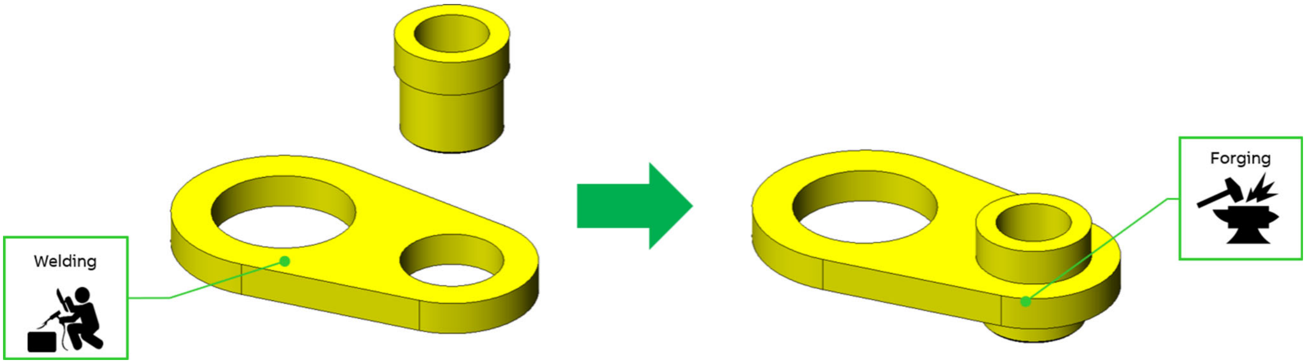


Fig. 9 Reducing part numbers

4.1 Results and next steps

4.1.1 Scalability and transferability of the framework

The proposed DfS framework was developed and validated within a large multinational manufacturing context characterized by advanced digital infrastructure, mature product development processes, and access to detailed environmental data. While this context enables a high level of analytical depth, the core logic of the framework is not inherently dependent on this scale of organization or resource availability. Indeed, several elements of the methodology are sector-agnostic and transferable across industrial contexts. These include hotspot-driven prioritization logic, the iterative integration of assessment and redesign activities, and the use of interdisciplinary collaboration to reconcile environmental objectives with technical and operational constraints. These principles can be applied to different product families, including those with low engineering complexity, provided that functional equivalence and life cycle boundaries are clearly defined.

For small and medium-sized enterprises (SMEs), the framework can be adapted by simplifying the data requirements and relying on screening-level LCA, sector-average datasets, or qualitative proxies during the early stages. The framework can be executed with a minimum dataset while preserving the decision logic. A practical "SME-lite" workflow is as follows:

(1) Product selection: choose one representative product based on sales/volume and a simplified BOM availability.
(2) Need definition: define the functional unit, system boundaries, and 2–3 explicit constraints (e.g., no change in safety–critical function, no new major equipment).
(3) Baseline model (screening): build a screening LCA using simplified BOM (e.g., top contributors by mass/cost) and generic datasets; document supplier location assumptions for key materials/processes.
(4) Hotspot refinement: identify the top 3–5 drivers and run 1–2 simple sensitivities on critical assumptions (e.g., material quantity, grid mix/location where relevant).
(5) Eco-design brainstorming (1–2h): run a short workshop with R&D + procurement/supplier representative using hotspot-based prompts; record ideas in a standardized template.
(6) Screening comparison: estimate the GWP change for shortlisted ideas using the same screening model and classify them using performance classes rather than exact values.
(7) Shortlist validation: perform a basic technical sanity check and select 3–5 concepts for deeper validation if needed. The objective is to preserve the decision logic and documentation trail even when data granularity is limited.

Although the resolution of environmental results may be lower for SMEs than for large enterprises, the decision logic remains valid and includes identifying dominant impact drivers, focusing design effort where leverage is highest, and documenting assumptions transparently. In this sense, the framework scales by preserving the decision structure under varying data availability rather than by replicating analytical depth.

At the same time, certain aspects are context dependent. Deep integration with enterprise systems using ERP or product lifestyle management and extensive simulation capabilities can enhance efficiency and robustness, but they are not prerequisites for methodological adoption. This distinction between core principles and enabling infrastructure is critical to ensure realistic transferability beyond large corporations.

4.1.2 From incremental eco-design to systemic industrial change

The proposed framework intentionally favors incremental innovation by focusing on component-level and architectural redesigns that can be implemented within existing industrial constraints. This orientation reflects the realities of engineering-intensive sectors, where safety, reliability, and certification requirements limit the feasibility of radical design changes. However, the incremental nature of the innovation should not be interpreted as a limitation; rather, it should be viewed as a necessary stepping stone toward broader system-level transformation. By embedding lifecycle thinking into routine design activities, the framework builds organizational capabilities, shared understanding, and internal legitimacy for sustainability-oriented decision making. These capabilities are widely recognized as prerequisites for more radical innovation pathways, including new product architectures, service-based models, or circular business strategies.

In this sense, the framework acts as a micro-level enabler of macro-scale sustainability transitions. Rather than proposing disruptive change exogenously, it supports endogenous transformation by progressively shifting design cultures, performance metrics, and decision criteria. This aligns with current transition-oriented literature that emphasizes the cumulative impact of incremental changes when supported by institutional learning and cross-functional collaboration.

4.1.3 Linking eco-design outcomes to value creation and business models

A central challenge for the industrial adoption of eco-design methodologies is the translation of environmental benefits into business value. In this study, economic assessment was deliberately deferred until after environmental and technical validation to avoid premature exclusion of promising concepts. While this sequencing supports creative exploration, it also raises questions regarding value-capture mechanisms.

The environmental improvements identified through the framework can generate value across multiple dimensions. For example, reduced life cycle emissions can mitigate regulatory and compliance risks, particularly in contexts characterized by tightening climate-related policies and disclosure requirements. Similarly, improvements in energy efficiency during the use phase can reduce operating costs for customers, thereby enabling differentiation through a lower total cost of ownership. Furthermore, documented environmental performance can enhance access to green procurement processes, sustainability-linked financing, and environmentally conscious market segments.

Beyond its product-level optimization, the framework creates opportunities for alignment with business model innovation strategies. For instance, design choices that enhance durability, reparability, and modularity can support service-oriented models, extended warranties, or product-as-a-service offerings. These models shift value creation from one-time sales to life cycle-based relationships to align economic incentives with environmental performance. In this respect, the framework complements existing research on circular business models by providing an operational mechanism that embeds sustainability criteria directly into design decisions.

4.1.4 Supply chain governance and resource implications

The case study highlights that a substantial share of environmental impacts originates upstream, particularly from raw material production and energy-intensive processes. While the framework primarily operates at the product and component design levels, the results demonstrate its potential to inform broader supply chain and sourcing strategies.

LCA hotspot analysis provides evidence for material substitution or process optimization, as well as for strategic supplier engagement. For instance, when specific materials have high embedded emissions, the framework can trigger supplier selection criteria based on energy mix, production technology, or geographic location. In this way, design decisions become connected to procurement policies and resource governance considerations.

This linkage is particularly relevant in the context of ongoing supply chain regionalization and decarbonization efforts. By integrating environmental performance into sourcing decisions, companies can simultaneously reduce transportation emissions, improve supply chain resilience, and support lower-carbon production ecosystems. The framework thus offers a structured pathway for extending DfS beyond organizational boundaries to aid the decarbonization of global value chains. These supply-chain considerations therefore feed back into Step 1 (product selection), Step 3–4 (scenario-based hotspot refinement), and Step 5 (supplier/regionalization options in brainstorming.

4.1.5 Methodological scope, limitations, and future extensions

The study deliberately focuses on GWP as the primary environmental indicator, as this reflects current market expectations and stakeholder priorities. However, while this focus enhances clarity and decision-making efficiency, it also introduces the risk of problem shifting, whereby improvements in climate performance may lead to unintended trade-offs in other impact categories. This limitation is explicitly acknowledged and addressed through the framework's modular structure, which allows the ready integration of additional impact categories in future iterations. Performing multicriteria lifecycle impact assessments and trade-off analyses becomes a natural extension of the methodology, particularly as data availability and organizational maturity increase.

Another limitation concerns the reliance on expert judgment during the qualitative screening and prioritization phases. While this introduces subjectivity, it also reflects the realities of early-stage industrial decision making. To reduce variability in the current implementation, the framework adopts a standardized technical-feasibility rubric for shortlisted concepts. Each concept is assessed across four dimensions: (i) functional risk, (ii) manufacturability/tooling impact, (iii) validation burden, and (iv) supply readiness. Each dimension is rated on a simple Low/Medium/High scale by the interdisciplinary team. Concepts showing one or more High-risk ratings are retained only as conditional and must undergo targeted validation before final selection. This rubric is applied during concept shortlist selection to make expert-based judgments more transparent and comparable across alternatives.

4.1.6 Implications for research and practice

From a research perspective, this study contributes a decision-oriented DfS framework that bridges the gap between assessment methodologies and industrial implementation. Rather than proposing new metrics or tools, it demonstrates how existing methods can be orchestrated into a coherent process that supports continuous improvement.

From a practical standpoint, the framework provides industrial practitioners with a replicable structure for embedding sustainability into design processes without disrupting existing workflows. Its flexibility allows adaptation across sectors and organizational scales, while its iterative nature supports long-term transformation rather than one-off optimization.

4.2 Research context and future steps in supply chain reorganization

Recent geopolitical events have underscored the need for resilient supply chains, prompting a move toward regionalization and closer partnerships that align with sustainability goals and the European energy transition. This shift aims to support the EU’s target of achieving over 70% renewable energy sources by 2050 and net-zero emissions. Based on the graphs shown in Fig. 10, which refer to the three years from 2022 to 2024, a comparative analysis of energy mixes across different regions reveals that while China leads in electricity production, its carbon intensity, along with that of India, remains high due to a reliance on fossil fuels. In contrast, the EU exhibits lower unit emissions, which are attributable to a cleaner energy portfolio that incorporates renewables, nuclear power, and efficient technologies. These differences highlight the significance of the energy mix in decarbonization strategies. Therefore, strategic decisions regarding supplier selection and relocation must consider the environmental impact of electricity and transportation.

Prioritizing suppliers who are geographically closer to manufacturing plants can substantially reduce CO_2 emissions associated with transportation. This approach offers logistical advantages, such as improved component management, reduced safety stock requirements, and leaner production processes with shorter lead times. Internal logistics, including warehousing and handling, also present opportunities for emission reduction through innovative packaging solutions. A comprehensive analysis of the entire supply chain, from procurement to distribution, provides the foundation for identifying and implementing targeted improvements.

5 Conclusion

This study proposes a structured Design for Sustainability framework that operationalizes Life Cycle Assessment within industrial product development through an iterative assessment–redesign loop. Rather than treating environmental assessment as an ex-post verification exercise, the framework uses hotspot evidence to refine design needs, guide concept generation, and support validation under real industrial constraints. The contribution of the paper therefore lies not in introducing new assessment tools, but in demonstrating how existing methods can be orchestrated into a decision-oriented and continuously improving industrial process.

Rather than introducing new assessment methods, this work contributes by demonstrating how the orchestration of existing tools into a coherent and iterative process can support continuous improvement. The key differentiator from linear eco-design models is that assessment does not remain a one-off diagnostic step, but repeatedly feeds back into need refinement, redesign ideation, and validation across successive iterations. By embedding Life Cycle Assessment hotspot analysis within a multistep design workflow, the framework enables interdisciplinary teams to identify environmental priorities, explore eco-design alternatives, and evaluate trade-offs in a manner that remains tightly aligned with real product development practices. The nine-step framework structure provides traceability between sustainability objectives, design decisions, and validated outcomes, thereby enhancing both transparency and replicability.

The demonstrated application to a medium-voltage circuit breaker confirms the framework’s practical viability in a high-complexity engineering context. The case study, which verifies that significant reductions in environmental impact can be achieved without compromising technical robustness, highlights the value of integrating early and systematic sustainability considerations into design activities.

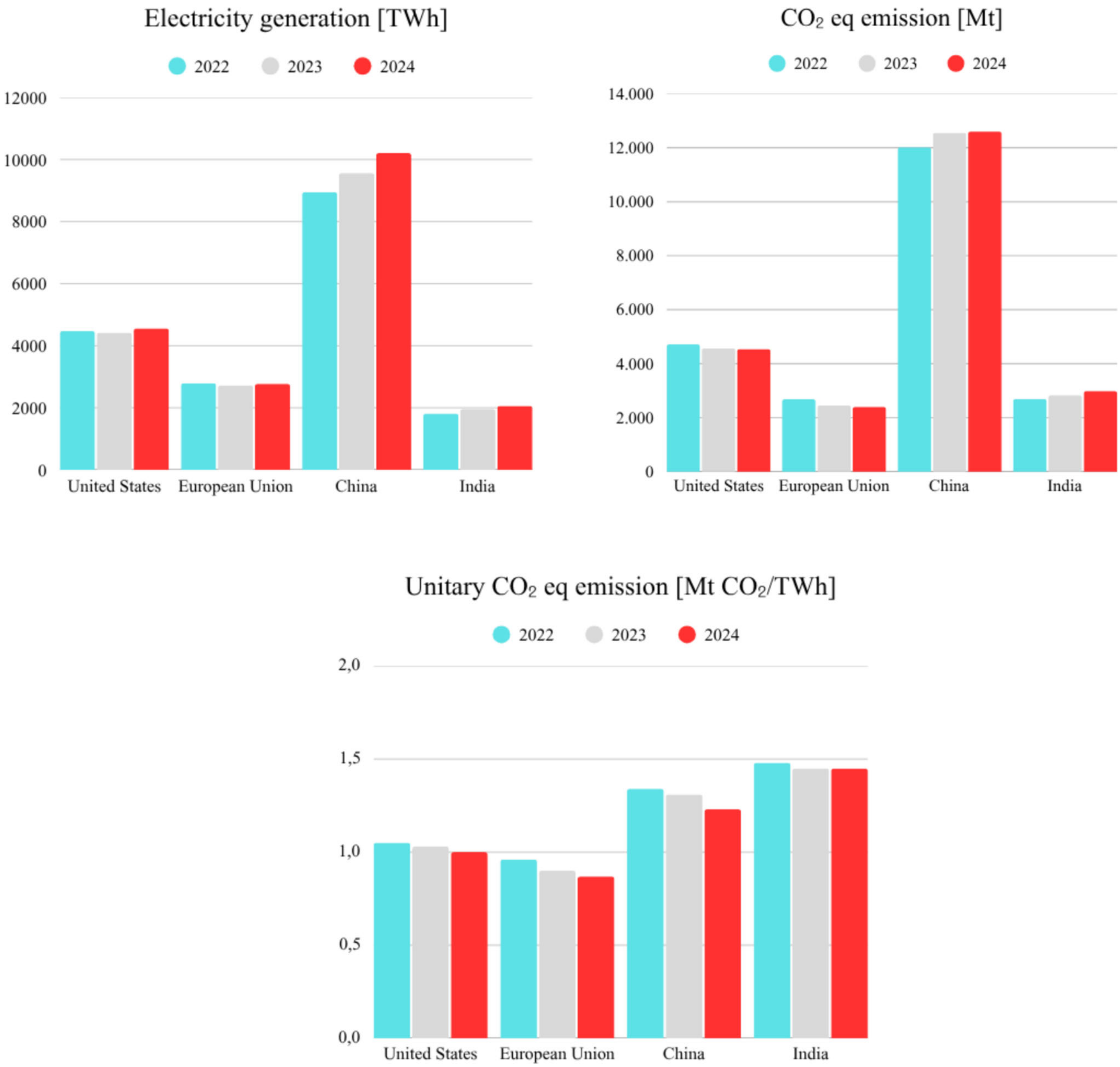


Fig. 10 Electricity generation; CO_2 eq. emissions; and unitary CO_2 eq. emissions for the three years from 2022 to 2024

Beyond individual redesign solutions, the process fosters cross-functional collaboration and knowledge transfer to reinforce sustainability as a shared design criterion rather than an external constraint. From a broader perspective, the proposed framework can be interpreted as a micro-level enabler of wide sustainability transitions in industrial systems. By operationalizing life-cycle thinking within everyday design decisions, the methodology contributes to organizational learning, capability building, and the gradual alignment of engineering practices with circular economy and decarbonization goals. Although the framework favors incremental innovation, these incremental changes represent a critical foundation for longer-term system-level transformation.

Several limitations must be acknowledged. The study focused primarily on Global Warming Potential as a response to current market and stakeholder priorities, with the awareness that single-impact optimization may lead to problem shifting. Moreover, to reflect the realities of industrial decision making under uncertainty, qualitative judgment remains necessary during early-stage screening and prioritization. That said, these limitations do not undermine the framework's validity, but instead define its scope and highlight opportunities for future extensions.

Future research should expand the methodology toward multicriteria life cycle impact assessments, deeper integration of economic evaluations, and systematic linkages between product-level design decisions and supply chain governance strategies. In particular, the use of Life Cycle Assessment evidence to inform supplier engagement and sourcing decisions represents a promising avenue for extending Design for Sustainability beyond organizational boundaries. Further validation across different sectors and organizational contexts, including small and medium-sized enterprises, would also strengthen the generalizability of the framework. This work demonstrates that a structured and iterative Design for Sustainability methodology can effectively bridge the existing gap between environmental assessment and industrial design practice. By aligning sustainability objectives with engineering workflows and decision-making processes, the framework provides researchers and practitioners with a practical pathway for embedding environmental performance as a core driver of industrial innovation.

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