



Guide for Manufacturing and Advanced Materials: Practicing LCA and Eco-Design

A Practical Framework for Sustainable Innovation

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Short Description

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Chapter 1: Introduction

1.1 Purpose of the Guide

Small and medium-sized enterprises (SMEs) in the composites and advanced material sectors are increasingly facing environmental, regulatory and market driven pressures to improve the sustainability of their products and processes. At the same time, many SMEs have limited internal resources, time or expertise to fully implement complex environmental assessment methodologies. The purpose of this guide is to support SMEs in getting started with Life Cycle Assessment (LCA) and Eco-Design practices in a practical, progressive and accessible way. It is designed as a hands-on reference, combining theoretical background with concrete examples, tools and use cases relevant to composite manufacturing.

This guide aims to:

- Demystify LCA and Eco-Design concepts for non-experts
- Provide structured guidance adapted to SMEs
- Help companies identify environmental hotspots in their products
- Support informed decision-making during product development
- Prepare companies for future regulatory and customer requirements.

Rather than promoting a one-size fit all approach, the guide encourages a step-by-step integration of sustainability thinking, starting with simplified tools and gradually moving toward more detailed assessments when needed.

1.2 Importance of Sustainability in Advanced Materials and Manufacturing

Industries

Manufacturing and advanced materials companies play a key role in many strategic sectors, including automotive, aerospace, construction, energy, textiles, plastics, chemicals, electronics, packaging and composite applications. These companies develop, transform or integrate materials into products with specific technical functions, performance requirements and value-chain constraints. Their activities offer significant opportunities for innovation, lightweight design, durability, resource efficiency and improved product performance. However, they are also associated with important environmental challenges, including:

- High energy consumption during raw material production, processing and transformation
- Use of fossil-based, non-renewable or critical raw materials
- Complex and multi-step manufacturing processes involving chemicals, heat, pressure, finishing or assembly operations
- Limited recycling, reuse and end-of-life options for multi-material or highly engineered products

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- Increasing waste streams from production scraps, off-cuts, rejected parts, packaging, chemicals or end-of-life products.

Sustainability is therefore becoming a critical competitiveness factor across the advanced materials and manufacturing ecosystem. Customers, original equipment manufacturers (OEMs), brand owners, public authorities and regulators increasingly expect transparent information about environmental performance, carbon footprint, resource use, circularity strategies and responsible supply chains.

For SMEs and industrial companies active in materials development, processing, manufacturing or product integration, integrating sustainability is not only a compliance issue but also an opportunity:

- Differentiation in increasingly sustainability-driven markets
- Cost reduction through material efficiency, energy savings and waste prevention
- Improved product design, process optimization and innovation
- Anticipation of upcoming regulations and customer requirements
- Strengthening customer relationships, supply-chain transparency and trust.

In this context, LCA and Eco-Design provide structured methodologies to quantify environmental impacts, compare materials, processes and product alternatives, identify hotspots, and support sustainable design choices throughout the product life cycle. They can be applied across different company profiles, from raw material suppliers and textile producers to component manufacturers, product developers, recyclers and advanced technology providers.

1.3 Overview of LCA and Eco-Design Principles

Life Cycle of assessment (LCA) is a standardized methodology used to evaluate the environmental impacts of a product, process or system throughout its entire life cycle, from raw material extraction to end-of-life. It allows companies to move beyond intuition or isolated indicators and adopt a life cycle thinking approach.

Eco-Design, on the other hand, focuses on integrating environmental considerations directly into product development and design decisions. It aims to minimize environmental impacts while maintaining functional technical and economic performance.

Together, LCA and Eco-Design form a complementary framework:

- LCA provides quantitative insights and hotspot identification
- Eco-Design translates these insights into practical actions.

This guide introduces both concepts in a way that is operational for SMEs, highlighting how they can be applied programmatically in composite product development workflows.

Chapter 2: Fundamentals of LCA

2.1 Definition and Scope of LCA

Defined by ISO14040, LCA (life cycle assessment) is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, it means that the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. It can be divided into 3 steps: 1) Compiling an inventory of relevant energy and material inputs and environmental releases, 2) Evaluating the potential environmental impacts associated with identified inputs and releases, 3) Interpreting the results to help you make a more informed decision [1,2].

2.2 Standards and Norms about LCA

LCA is supported by several international standards and methodological frameworks that define how environmental assessments should be conducted, reported and communicated. These standards ensure transparency, consistency and comparability between studies. Table 1 shows the definitions between different standards.

Table 1. Standards and norms for LCA

Standard / framework	Main purpose	Relevance for LCA
ISO 14040 ISO 14044	Principles and framework, requirements and guidelines	ISO 14040 establishes the principles and overall framework of LCA, whereas ISO 14044 specifies the detailed requirements and guidelines for conducting the four LCA phases, reporting and critical review [1,2].
ISO 14025	Type III environmental declarations	Defines principles and procedures for Environmental Product Declarations based on LCA.
PCR	Product Category Rules	Provides product-specific rules to ensure comparable LCA and EPD results within the same product category PCR: a standardized LCA recipe
EPD	Environmental Product Declaration	Communicates verified LCA-based environmental information (report) for a product. It typically takes into consideration your full value chain, from material extraction to manufactured product, its usage stage and end of life. From < https://www.environdec.com/all-about-epds/the-epd > EPD: a ISO type III Environmental Declaration final Report
EN 15804	Construction product EPDs	Defines core rules for EPDs of construction products in Europe.
ISO 21930	Sustainability in buildings and civil engineering works	Provides rules for environmental declarations of construction products and services.
PEF	Product Environmental Footprint	EU-recommended LCA-based method for measuring the environmental performance of products. From < https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html >

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OEF	Organisation Environmental Footprint	EU-recommended method for assessing the environmental performance of organisations.
PEFCR	Product Environmental Footprint Category Rules	Provides product-category-specific rules for applying the PEF method. PEFCRs define modelling requirements, functional units, system boundaries, data quality rules, impact assessment requirements and benchmarks to improve consistency and comparability between products within the same category.

In practice, ISO 14040 and ISO 14044 are the **foundations** for conducting an LCA. When the objective is to communicate results externally, for example through an Environmental Product Declaration, additional rules such as ISO 14025, PCRs and sector-specific standards must be followed. In Europe, the PEF method is increasingly important because it aims to **harmonize environmental footprint calculations** and improve comparability between products. For specific product categories, PEFCRs provide detailed rules on how the PEF method should be applied, in a similar way to PCRs for EPDs.

2.3 Key Phases of LCA: Goal and Scope Definition, Inventory Analysis, Impact assessment, Interpretation

According to ISO 14040 and ISO 14044, LCA is based on 4 main phases (as in figure 1): 1) goal and scope 2) inventory analysis, 3) impact assessment, 4) interpretation.

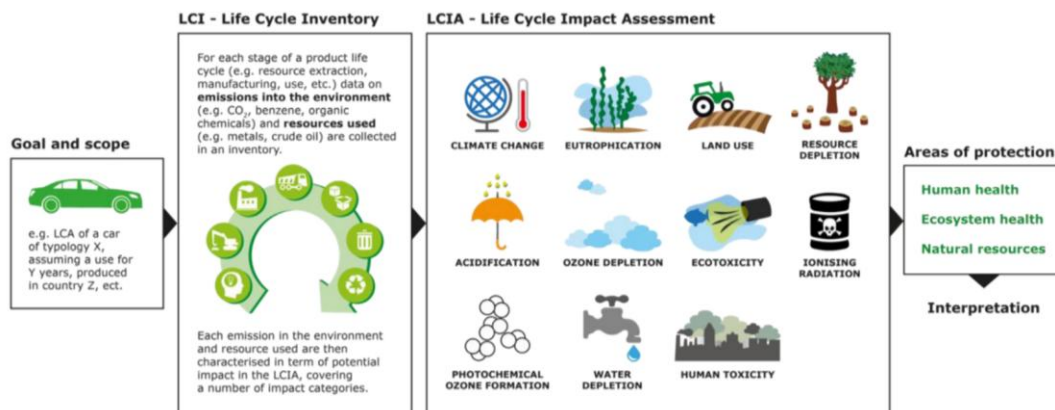


Figure 1. Life Cycle Assessment steps: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation [3].

1) Goal and Scope

In the goal and scope phase, the aims of the study are defined, namely the intended application, the reasons for carrying out the study and the intended audience. Main methodological choices are made in this step, in particular the exact definition of the functional unit, the identification of the system boundaries, the identification of the allocation procedures, the studied impact categories and the Life Cycle Impact Assessment (LCIA) models used, and the identification of data quality requirements.

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2) Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase involves the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system. Inputs and outputs concern energy, raw material and other physical inputs, products and co-products and waste, emissions to air/water/soil, and other environmental aspects. Data collected concern foreground processes (e.g. for a consumer good manufacture, the manufacturing and packaging of a product) and background processes (e.g. the production of purchased electricity and materials). Data is validated and put in relationship to the process units and functional units.

3) Life Cycle Impact Assessment (LCIA)

In the Life Cycle Impact Assessment (LCIA) phase, LCI results are associated with environmental impact categories and indicators. This is done through LCIA methods which firstly classify emissions into impact categories and secondly characterize them to common units so as to allow comparison (details on the LCIA method are presented in the section below).

4) Life Cycle Interpretation phase

Finally, in the Life Cycle Interpretation phase, results from LCI and LCIA are interpreted in accordance with the stated goal and scope. This step includes completeness, sensitivity and consistency checks. Uncertainty and accuracy of obtained results are also addressed in this step.

2.4 Impact Assessment (LCIA) method

The LCIA method is essential in an LCA study because it defines the impact categories, characterization factors and calculation rules used to assess potential environmental impacts. For example, greenhouse gas emissions are converted into kg CO₂ equivalent for the climate change indicator. Other impact categories may include acidification, eutrophication, human toxicity, ecotoxicity, water use and resource depletion, as shown in Fig. 1. International standards such as ISO 14040 and ISO 14044 define the overall LCA framework, but they do not prescribe a single LCIA method; therefore, practitioners must select a method that is appropriate for the goal, scope, geographical context and communication needs of the study. Commonly used LCIA methods include Environmental Footprint EF 3.1, ReCiPe 2016, IMPACT 2002+ and ILCD 2011 Midpoint+, as summarized in Table 2. European Commission/JRC reports provide the methodological basis for the Environmental Footprint method and its updated EF 3.1 characterization and normalization factors [4]; Huijbregts et al. describe ReCiPe 2016 as a harmonized LCIA method linking midpoint and endpoint indicators [5]; Jolliet et al. present IMPACT 2002+ as a combined midpoint/damage approach [6]; and the ILCD handbook provides recommended characterization factors for European LCIA practice [7].

Table 2. Comparison of commonly used LCIA methods.

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Method	Main Purpose	Geographic Scope	Impact Categories	Strengths	Typical Applications
EF 3.1 (Environmental Footprint)	Harmonized environmental assessment developed by the European Commission	Europe	16 midpoint impact categories	Strong alignment with EU policies and Product Environmental Footprint (PEF) requirements; high comparability between products	Product Environmental Footprint (PEF), eco-design, EU-funded projects, sustainability reporting
EN 15804 + A2	Environmental assessment of construction products	Europe	Environmental indicators required for EPDs	Standardized methodology for construction products and Environmental Product Declarations (EPDs)	Construction materials, building products, EPD development
ReCiPe 2016	Comprehensive environmental impact assessment	Global	Midpoint and endpoint indicators	Widely used internationally; provides both detailed environmental mechanisms and aggregated damage indicators	Research, product comparison, eco-design, innovation projects
IPCC Global Warming Potential (GWP)	Climate change assessment	Global	Climate change only (kg CO ₂ eq)	Simple, robust and easily communicated	Carbon footprint studies, corporate reporting, preliminary screening
IMPACT 2002+	Integrated midpoint and endpoint assessment	Global	Multiple midpoint and endpoint categories	Combines environmental mechanisms and damage-oriented results	Research studies, scenario analysis, strategic decision support
ILCD 2011 Midpoint+	European reference impact assessment framework	Europe	Multiple midpoint categories	Strong scientific basis and transparency; predecessor of EF methods	Historical studies, literature comparison, older EU projects

In practice, for SMEs seeking to integrate sustainability into product development and prepare for evolving European regulatory requirements, EF 3.1 currently represents the most relevant and future-oriented methodology. EF 3.0. was used between 2018 and 2022. EF 3.1 is the current version recommended by the European Commission and represents an update of EF 3.0.

References

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Chapter 3: Eco-Design Principles

3.1 What is Eco-Design?

AFNOR (French Standardization Association) defines Eco-Design as integrating environmental considerations from the beginning of product or service design and throughout all stages of its life cycle, based on life cycle assessment [8].

The ISO 14006 standard defines Eco-Design: "a systematic approach that integrates environmental aspects into the product design and development process with the aim of reducing negative environmental impacts throughout a product's life cycle."

3.2 Benefits for Advanced Materials and Manufacturing Companies

Eco-design encompasses the development and manufacture of a product while addressing its functional and aesthetic characteristics. It aims to meet user needs while improving environmental performance without compromising economic viability. By adopting a strategic and organizational approach, eco-design integrates sustainability considerations throughout product development, production, use, and end-of-life management. It focuses on reducing environmental impacts across the entire life cycle, while considering potential

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impact transfers between life cycle stages. At the same time, it supports competitiveness, innovation, and continuous improvement by encouraging the development of high-quality products that maintain functionality, reliability, and aesthetic appeal, ultimately contributing to more sustainable and resource-efficient value chains.

3.3 Integration with Product Development

The eco-design approach consists of deploying the three steps of evaluating, improving and communicating the environmental performance of a product, process or service.

Example: Bamboo toothbrushes. Bamboo toothbrushes (Fig.2) are a well-known example of eco-design based on material substitution and improved end-of-life management. Instead of using a conventional plastic handle, which is made from fossil-based resources and must be properly recycled to avoid landfill or environmental leakage, the handle is made from bamboo, a fast-growing and renewable material. At end of life, the bamboo handle can be composted under suitable conditions, while the bristles or other non-biodegradable parts should be separated and managed through appropriate waste routes. According to LCA studies comparing different toothbrush options, bamboo toothbrushes generally show lower environmental impacts than conventional plastic toothbrushes across most impact categories, mainly because of their reduced material-related impacts and the use of a renewable biogenic resource [10].



Figure 2. Eco-design example of a bamboo toothbrush: replacing fossil-based plastic with renewable bamboo and improving end-of-life through composting of the handle.

3.4 Eco-Design Checklist and Guideline

The following checklist provides a simple step-by-step framework to help companies start an eco-design approach for a selected product, process or service. It guides the project team from preparation and training to the identification of a reference case, the first environmental assessment, the implementation of improvement options, the second assessment, and finally the communication of verified environmental performance [9].

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1. **Preparation:** Set up a cross-functional project team, because eco-design involves all company functions, including marketing, sales, purchasing, design, production, innovation and R&D.
2. **Training:** Train yourself and the project team on eco-design principles, life cycle thinking and the basic use of LCA tools.
3. **Identification:** Select the reference product, process or service to be assessed and improved.
4. **First LCA:** Carry out a first environmental assessment of the reference product, process or service to identify the main environmental hotspots.
5. **Improvement:** Identify, evaluate and implement improvement options, such as material substitution, process optimization, waste reduction, improved durability or better end-of-life management.
6. **Second LCA:** Perform a new environmental assessment to compare the improved solution with the initial reference and verify whether the expected environmental gains are achieved.
7. **Communication:** Communicate the environmental performance of the eco-designed product, service or process in a transparent and evidence-based way.

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Chapter 4: Tools and Methodologies

4.1 LCA Software and Tool

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LCA tools can be grouped into several families, depending on the level of detail required, the user's expertise, the available data and the objective of the assessment. No single tool is suitable for all companies or all applications. A small company starting its sustainability journey may need a simple screening tool to identify environmental hotspots, while a company preparing an Environmental Product Declaration or a detailed comparative LCA will need a professional tool with transparent modelling, recognized databases and compliance with international standards. The LCA tool overview is based on official information from ADEME Base Empreinte® and Bilan Produit® [12], Ecochain Mobius [13], SimaPro by PRé Sustainability [14], openLCA by GreenDelta [15], Sphera LCA for Experts [16], One Click LCA [17], IPC C3R'IMPACT [18], and Conbility OPLYSIS-eco [19].

In this guide, the objective is to evaluate different company profiles and identify the most suitable LCA tools for each profile. Three levels of maturity are considered:

- **Company profile 1** : This profile represents SMEs with little or no previous experience in Life Cycle Assessment (LCA) or eco-design. These companies typically have limited financial and human resources and require a solution that is affordable, intuitive, and easy to implement.
- **Company profile 2** : This profile represents SMEs that have already gained initial experience with LCA and wish to integrate environmental considerations into product development and decision-making. These companies require a balance between usability and analytical capability
- **Company profile 3** : This profile represents organisations with experienced LCA practitioners or dedicated sustainability teams conducting detailed environmental assessments. Their priority is obtaining accurate, transparent, and standards-compliant results suitable for professional applications

4.2 KPIs definition and Tool evaluation

To compare several LCA tools available on the market, the evaluation is based on a set of practical Key Performance Indicators (KPIs) and multi-criteria evaluation matrix developed within the SMARAGD project. The objective of this evaluation is to benchmark LCA tools that are suitable for small and medium-sized enterprises (SMEs). The assessment supports the selection of appropriate tools within the SMARAGD project by comparing their functionality, usability, and suitability for different user groups.

The KPIs are first defined according to the requests of SMEs received within the project. These KPIs assess not only the environmental modelling capacity of the tools, but also their cost, usability, database coverage, transparency, standards compliance and suitability for different company profiles. As shown in Table 3, the KPIs are defined and the relevance for selecting LCA tool. A weighting value is given to each KPI for different company profiles. The

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weighting is expressed on a scale from 1 to 10, and given to each criterion changes according to the expected user maturity, and their priorities, beginner SMEs give more importance to cost, ease of use and support, while professional users give more importance to methodological transparency, database completeness, custom modelling and compliance with standards, as defined in Table 4. Table 5 shows the weighting of evaluation criteria for different company profiles.

Table 3. KPIs used to evaluate LCA tools.

KPI	Definition / What is evaluated	Relevance for selecting an LCA tool
Cost	Purchase price, licence fee, subscription cost, database access cost, training cost and maintenance cost.	A key criterion for SMEs and first-time users with limited budgets.
Quality and completeness of results	Level of detail, reliability, accuracy and completeness of the environmental results generated by the tool.	Important for ensuring that results are meaningful enough for decision-making, reporting or communication.
Visualization and use of results	Capacity to present results through graphs, dashboards, contribution analyses, hotspots, scenario comparisons and exportable reports.	Helps users understand results and translate them into eco-design or business decisions.
User friendliness and technical support	Availability of guidance, tutorials, helpdesk support, documentation, training material and responsive technical assistance.	Essential for non-expert users and companies building internal LCA competence.
Ease of use	Simplicity of the interface, clarity of the workflow, time required to build a model and level of LCA expertise required.	Determines whether the tool can be used efficiently by SMEs, designers, engineers or non-specialists.
Completeness of databases	Coverage and quality of available datasets, including materials, processes, energy, transport, end-of-life scenarios and sector-specific data.	Affects the representativeness and reliability of the LCA results, especially for advanced materials and manufacturing processes.
Possibility to perform comparative LCA	Ability to compare products, materials, processes, scenarios or design alternatives under consistent assumptions.	Useful for eco-design, material selection, process optimization and customer-oriented comparisons.
Compliance with standards	Compatibility with recognized standards and frameworks such as ISO 14040/14044, ISO 14025, PEF, EN 15804 or EPD requirements.	Critical when results are intended for external communication, certification, EPDs or regulatory compliance.
Ability to add custom calculations	Possibility to create user-defined processes, parameters, formulas, allocation rules, indicators or specific modelling assumptions.	Important for advanced users, research applications and innovative materials or technologies not covered by default databases.
Language availability	Availability of the software interface, documentation, reports and support in different languages.	Improves accessibility for SMEs, multilingual teams and companies working with local staff or international partners.
Transparency of calculation	Clarity of assumptions, emission factors, datasets, calculation methods, allocation rules and result traceability.	Supports credibility, reviewability and trust in the results, especially for professional or external studies.

Table 4. KPI weighting score scale according to company requirements.

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Weighting score range	Priority level for the company profile	Interpretation for tool selection
1-2	Very low-priority requirement.	The KPI is not essential for this company profile and has limited influence on the final tool recommendation.
3-4	Low to moderate priority requirement.	The KPI is useful but not decisive; it may support the selection only when several tools have similar overall suitability.
5-6	Medium priority requirement.	The KPI is relevant for the company profile and should be considered in the tool comparison, but it is not the main selection driver.
7-8	High priority requirement.	The KPI is important for this company profile and has a strong influence on the suitability score of each tool.
9-10	Very high or critical priority requirement.	The KPI is a key requirement for this company profile and should strongly determine the recommended LCA tool.

Table 5. Weighting of evaluation criteria for different company profiles.

Evaluation criteria	Profile 1 – Beginner SME	Profile 2 – Intermediate level	Profile 3 – Professional LCA user
Cost	10	7	1
Quality and completeness of results	5	8	5
Visualization and use of results	5	8	5
User friendliness and technical support	5	7	3
Ease of use	10	8	1
Completeness of databases	5	5	8
Possibility to perform comparative LCA	2	5	4
Compliance with standards	2	3	10
Ability to add custom calculations	1	2	8
Language availability	5	5	5
Transparency of calculation	2	5	8
Total weight	50	63	58

Final assessment of LCA tools

Based on the evaluation criteria defined Table 5, each LCA tool was assessed using a rating scale from 1 to 5, where 1 represents the lowest and 5 the highest performance. The ratings were assigned based on the results of the tool evaluation, including the available functionalities, database coverage, usability, transparency, and other relevant characteristics. The rating for each criterion was then multiplied by the corresponding weighting factor defined for each company profile. The resulting weighted scores were summed to obtain the final score for each tool (Table 6, a, b & c). The summary of recommended LCA tools by company profile is shown in Table 7.

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Table 6a. Final assessment of LCA tools for Profile 1 – Beginner SME.

LCA Tool	Weighted Score	Rank
C3R	185	1
Oplysis-Eco	178	2
Idemat	177	3
Oplysis-Eco with support package	173	4
openLCA	143	5
SimaPro	141	6

Table 6b. Final assessment of LCA tools for Profile 2 – Intermediate Level.

LCA Tool	Weighted Score	Rank
C3R	226	1
Oplysis-Eco	212	2
Oplysis-Eco with support package	212	2
Idemat	198	4
SimaPro	168	6
openLCA	169	5

Table 6c. Final assessment of LCA tools for Profile 3 – Professional LCA User.

LCA Tool	Weighted Score	Rank
SimaPro	258	1
openLCA	245	2
C3R	193	3
Oplysis-Eco with support package	184	4
Oplysis-Eco	182	5
Idemat	158	6

4.3 Tool selection

The following categories can be used as a practical starting point for selecting tools, :

- **Simplified or screening LCA tools:** suitable for non-expert users and beginner SMEs that need rapid hotspot identification, early eco-design support and first comparisons between design alternatives. Examples include C3R Impact, Bilan Produit and sector-specific calculators.

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- **Product footprint and guided LCA platforms:** suitable for intermediate companies that want to model products more systematically, compare scenarios, use primary data and generate visual outputs for internal decision-making or customer communication. Examples include Ecochain Mobius and similar guided platforms.
- **Process-oriented eco-efficiency tools:** suitable for manufacturing companies that need to compare process chains, resource consumption, operational costs and environmental impacts at the same time. OPLYSIS-eco is an example of this type of tool.
- **Professional LCA software:** suitable for advanced users, consultants, research centres and companies preparing detailed LCA studies, EPDs, PEF studies or scientific publications. Examples include SimaPro, openLCA and GaBi/Sphera.
- **Sector-specific compliance tools:** suitable for industries with strong regulatory or market requirements, such as construction and building products, where tools such as One Click LCA can support building LCA, product EPDs and compliance with sector standards.

Table 7. Summary of recommended LCA tools by company profile.

Company Profile	Recommended Tools
Profile 1 – Beginner	Idemat, C3R Impact, Bilan Produit (Base Empreinte)
Profile 2 – Intermediate	Ecochain Mobius, Conbility (Oplysis-Eco), C3R Impact
Profile 3 – Professional	SimaPro, GaBi, openLCA, One Click LCA

4.4 Typical tool introduction

SIMPLIFIED LCA TOOLS: C3R'IMPACT

C3R'IMPACT is a simplified Life Cycle Assessment (LCA) software developed by CT IPC (French Technical Center for Plastics and Composites) in collaboration with EVEA. It is specifically designed to help companies in the plastic and composites sectors perform environmental assessments without requiring advanced LCA expertise. C3R Impact follows a structured life cycle-based workflow composed of the following steps (Fig. 3).

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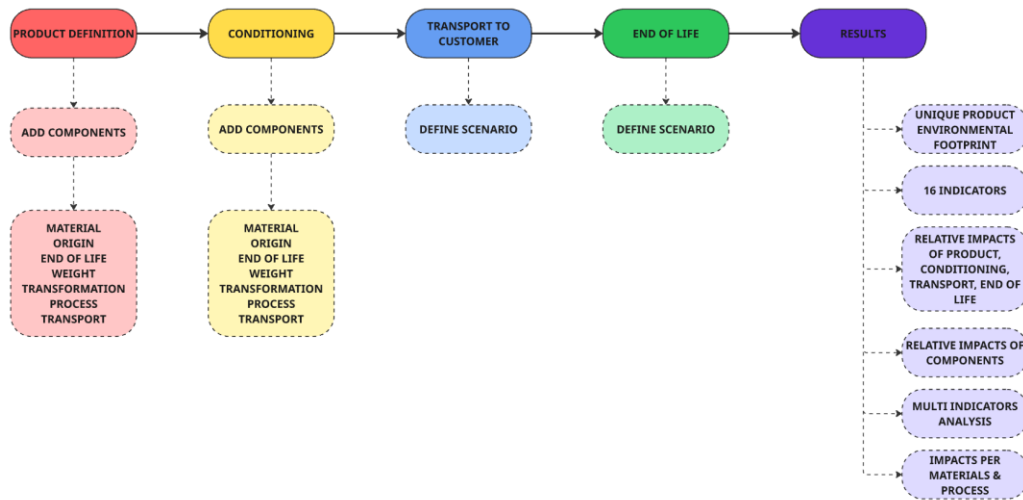


Figure 3. C3R'IMPACT workflow for product definition, transport, end-of-life modelling and environmental result generation.

- Product definition**
 The user defines the product by selecting the materials, manufacturing processes, and specifying the origin, including associated transport.
- Conditioning**
 The packaging or conditioning of the product can be defined at this stage, although it may not be relevant for all use cases.
- Transport scenario**
 The user specifies the transport modes (plane, boat, truck, train) and the corresponding travel distances.
- End-of-life scenario**
 The end-of-life treatment is defined by allocating percentages to recycling, landfill, and incineration, for each family of materials.
- Results generation**
 The tool calculates environmental impacts and provides a single aggregated score based on 16 indicators (e.g., resource use, climate change, eutrophication, human toxicity), along with a breakdown of the relative contribution of each life cycle stage (materials, processes, transport, etc.), enabling hotspot identification.

Overall, C3R Impact illustrates how simplified LCA tools translate life cycle thinking into a structured yet accessible workflow. By guiding users step by step and providing both an aggregated score and detailed environmental indicators, the tool makes it possible to quickly identify environmental hotspots and compare design alternatives. While the results remain screening-level and depend on predefined methodological choices and database

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coverage, such tools offer a practical and efficient entry point into LCA. They therefore play a key role in supporting informed decision-making at early development stages and in progressively building internal competence in environmental assessment.



Process-oriented eco-efficiency tool - OPLYSIS-eco

Process-oriented eco-efficiency tools represent a second category of LCA tools. They are designed for companies that want to analyse not only the environmental impacts of a product or process, but also the operational resources and costs associated with each manufacturing step. This type of tool is particularly relevant for industrial process optimization, where decisions often require balancing environmental performance, production efficiency and economic feasibility. In this guide, OPLYSIS-eco is used as an example of a process-oriented tool that combines environmental assessment with cost and resource analysis.

OPLYSIS-eco follows a structured process-based workflow composed of the following steps in Fig. 4.

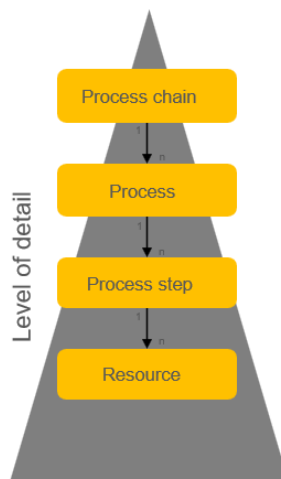


Figure 4. OPLYSIS-eco process-oriented workflow for resource allocation, environmental and cost assessment, and scenario analysis.

- Process chain definition**
 The overall system is modelled by defining the process chain and linking the different processes and process steps involved in the production or recovery pathway.
- Resource allocation**
 Relevant resources and operational parameters are assigned to each process step, including material flows, energy demand, water use, chemicals, transport, and equipment utilisation.

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- **Environmental impact calculation**
The tool calculates environmental impacts based on life cycle inventory data and selected environmental indicators such as climate change potential, resource use, emissions, and waste generation.
- **Cost and eco-efficiency assessment**
In parallel with the environmental analysis, process-related costs are calculated to evaluate eco-efficiency and identify trade-offs between environmental and economic performance.
- **Hotspot and scenario analysis**
The contribution of individual processes and resources can be analysed to identify environmental and economic hotspots. Alternative process configurations and improvement scenarios can also be compared to support optimization and decision-making.

Overall, OPLYSIS-eco demonstrates how process-oriented LCA tools can support sustainable process development through the integration of environmental and economic assessments within a single modelling environment.

SímaPro

Professional LCA software tool - Simapro

Professional LCA software tools, developed by Pré sustainability are intended for experienced users who need detailed, transparent and standards-compliant environmental assessments. They allow practitioners to build complete life cycle models, define system boundaries, select databases and impact assessment methods, document assumptions, and perform sensitivity or scenario analyses. These tools are suitable for research projects, comparative LCAs, Environmental Product Declarations, Product Environmental Footprint studies and other applications requiring robust and traceable results. In this guide, SimaPro is presented as an example of a professional LCA software tool widely used by researchers, consultants and industrial sustainability teams, as shown in Fig. 5.

SimaPro is used in many domains, particularly relevant to your work:

- **Product eco-design**
Comparing alternative materials (e.g., carbon fiber vs recycled composites)
- **Carbon footprint calculation**
Estimating greenhouse gas emissions (kg CO₂ eq)
- **Research and innovation projects**
Supporting sustainability assessment in EU projects (Horizon Europe, CORNET, etc.)
- **Environmental Product Declarations (EPDs)**
Generating standardized environmental reports

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- **Policy and decision support**
Helping industries reduce environmental impacts

Turning Data into Action

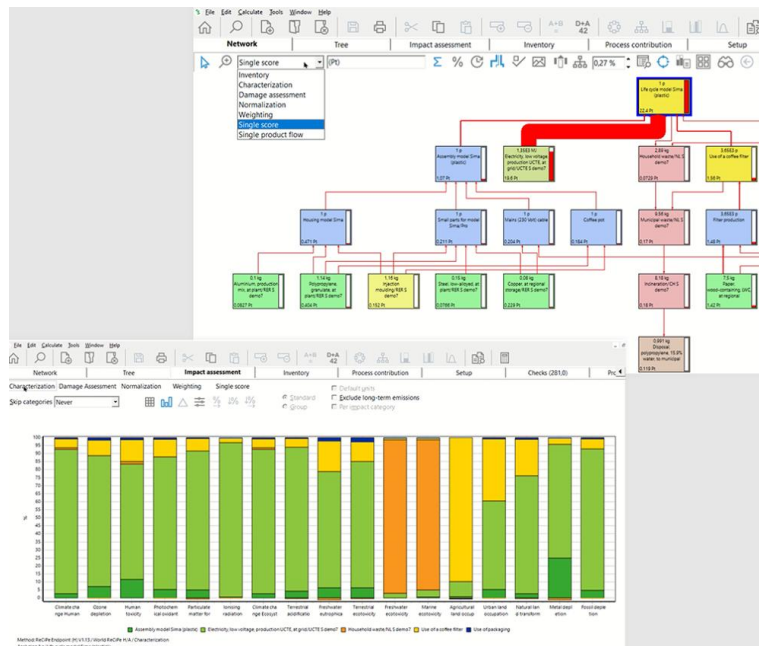


Figure 5. SimaPro professional LCA software used to turn inventory data into environmental assessment results and decision support.

4.5 Database of LCA

LCA software tools rely on background databases to model materials, energy, transport, manufacturing processes, waste treatment and end-of-life scenarios. The choice of database has a strong influence on the quality, representativeness and transparency of the results. Some databases are generic and multi-sectoral, while others are sector-specific, for example for agriculture, food, plastics, construction, or regional markets. In practice, professional LCA tools such as SimaPro, openLCA and Sphera/GaBi can use several databases, whereas simplified tools often rely on embedded or pre-selected datasets. Examples of LCA databases that can be used with LCA tools shows in Table 8.

Table 8. Examples of LCA databases that can be used with LCA tools.

Database	Main scope	Typical use	Examples of compatible tools
ecoinvent	Generic multi-sector life cycle inventory database covering energy, materials, chemicals, transport, waste, metals, textiles, forestry, agriculture and other sectors.	Frequently used as a background database for product LCA, eco-design, carbon footprinting, PEF studies, EPDs and research projects.	SimaPro, openLCA, Sphera/GaBi and other professional LCA platforms.

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Sphera Managed LCA Content / GaBi databases	Large professional database system with industry-driven datasets for energy, materials, chemicals, packaging, electronics, transport and other sectors.	Suitable for professional studies, EPD preparation, product carbon footprints, enterprise LCA and industrial decision-making.	Mainly Sphera LCA for Experts / GaBi.
ELCD / European Life Cycle Data Network	European reference data for key materials, energy carriers, transport and waste management.	Useful for European studies, historical comparison and studies aligned with European Commission LCA practice.	openLCA, SimaPro and ILCD-compatible tools.
Plastics Europe Eco-profiles	Life cycle inventory datasets and eco-profile reports for common plastics and polymer production in Europe.	Relevant for plastics, composites, packaging, polymer materials and material substitution studies.	openLCA, SimaPro and tools able to import ILCD or compatible dataset formats.
Agri-footprint	Agricultural and food-related life cycle inventory database for crops, feed, food, biomass and bio-based products.	Useful for bio-based materials, natural fibres, biomass feedstocks, food packaging and agri-food supply chains.	SimaPro and openLCA.
AGRIBALYSE	French agricultural and food LCA database developed for agricultural and food products produced and/or consumed in France.	Useful for food products, bio-based feedstocks, consumer products with agricultural ingredients and French food-sector eco-design.	SimaPro, openLCA and Brightway implementations.
World Food LCA Database	International database for agri-food products with global coverage of agricultural and food-related datasets.	Relevant for global food, agricultural and bio-based supply chains, including land, water and carbon-related impacts.	SimaPro and dedicated Quantis/eQosphere workflows.

For SMEs, the database should be selected according to the sector, geographical relevance, required level of precision and purpose of the study. For a first screening assessment, embedded datasets in simplified tools may be sufficient. For external communication, comparative assertions, EPDs or PEF-oriented studies, the database choice must be documented carefully and should rely on recognized, up-to-date and transparent sources.

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Chapter 5: Use Case Studies in Composite Manufacturing and Advanced Materials

This chapter translates the LCA and eco-design principles presented in the previous chapters into four practical industrial case studies covering electronics, composite manufacturing, recycled carbon-fibre products and mono-material textiles. Each use case follows a common structure—scope and method, inventory, impact assessment and interpretation—to show how different assessment tools and levels of detail can support decision-making. The external smartphone battery demonstrates rapid hotspot identification with the simplified C3R'IMPACT tool; the GFRP leaf spring illustrates combined environmental and economic process analysis with OPLYSIS-eco; the recycled carbon-fibre plate with T-stiffener applies a detailed SimaPro model to quantify the benefits of prepreg reuse; and the mono-material PET carpet case examines recycling allocation through the Circular Footprint Formula within the PEF framework. Together, these examples demonstrate how companies can progressively apply LCA, from early screening and process optimization to detailed comparative assessment, sensitivity analysis and circular-design evaluation.

5.1 Use Case 1 – External Smartphone Battery

Scope and method

Evaluate the environmental impact of an external smartphone battery pack using the **C3R Impact** simplified life cycle assessment (LCA) tool, as presented in Fig. 6. The objective is to identify the components and life cycle stages that contribute most to the product's environmental footprint, compare design alternatives, and highlight opportunities for eco-design and circularity. The product assessed is an external smartphone battery pack composed of plastic housing, an electronic board, and a customized aluminum cover. The assembly is fastened with screws and is fully

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disassemblable. Table 9 below summarizes the composition of the assembly, along with the associated materials and manufacturing processes.



Figure 6. External smartphone battery pack assessed with the C3R'IMPACT simplified LCA tool.

Inventory Analysis (LCI)

Table 9. Material composition, manufacturing processes and transport assumptions for the external smartphone battery pack.

POWERBANK SIRRIS					
Part	Material	Weight [g]	Quantity	Process	Transport to assembly location
Top cover	Aluminum (30-50% recycled)	164	1	Aluminium forming Laser machining Anodisation	Truck - 50 km
Upper casing	ABS (virgin)	70	1	Injection moulding	0
Lower casing	ABS (virgin)	58	1	Injection moulding	0
Insert	Brass	0.6	4	Machining (turning)	Plane 9000 km + Truck 100 km
Casing screws	Stainless steel	1.2	4	Cold forming	Plane 9000 km + Truck 100 km
PCB screws	Stainless steel	0.58	3	Cold forming	Plane 9000 km + Truck 100 km
PCB	FR4	30	1	PCB production (etching, drilling)	Plane 9000 km + Truck 100 km

The simplified life cycle assessment tool C3R Impact makes it possible to model the product and its various components by defining, for each of them:

- The quantity
- A supply transport step, if production and assembly are not carried out at the same site

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- The number of reuses
- The materials, their origin, and quantities
- The transformation and finishing processes in a selected country

For this product, the software makes it possible to visualize the impact of the different components, computed according to method EF 3.1, using both a single score and various criteria such as:

- Climate change
- Resource use (metals and minerals)
- Fossil resource use
- Fine particulate matter
- Water eutrophication
- Human toxicity

In addition, the software provides eco-design indicators such as recycled material content and recyclability potential, while enabling the contribution of individual components and materials to be visualized.

Impact Assessment (LCIA)

This assessment makes it possible to compare different external battery models with one another, while also identifying the most impactful components. These should therefore be considered the priority areas to explore in order to reduce the product's environmental impact (Fig. 7 – Fig. 10).

As an example, the external battery studied shows impacts mainly related to climate change and the use of resources, including metals, minerals, and fossil resources.

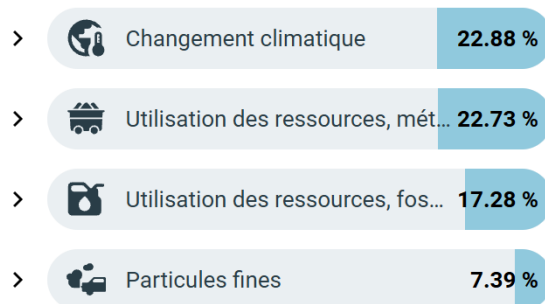


Figure 7. Environmental impact profile of the external smartphone battery across the EF 3.1 impact categories.

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It can then be observed that customized aluminum cover is the most impactful component with regard to climate change, for example.

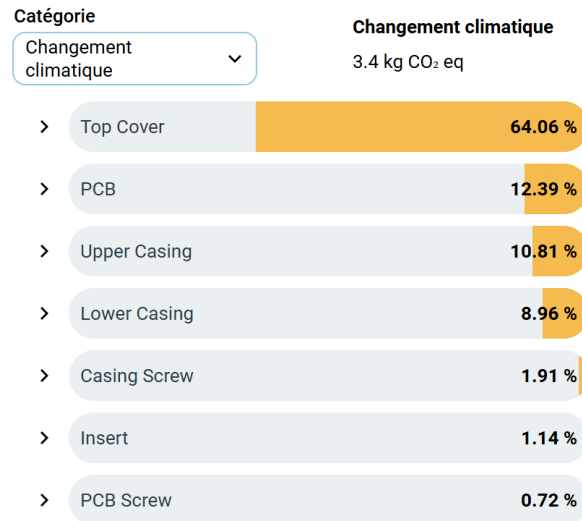


Figure 8. Contribution of the battery components to climate change impact, highlighting the customized aluminium cover.

In addition, design indicators provide information in particular on the share of recycled material in the assembly and on the product's recyclability potential.



Figure 9. Eco-design indicators for recycled material content and product recyclability potential.

Other visualizations make it possible to identify that materials account for the largest contribution to impacts according to the different criteria.

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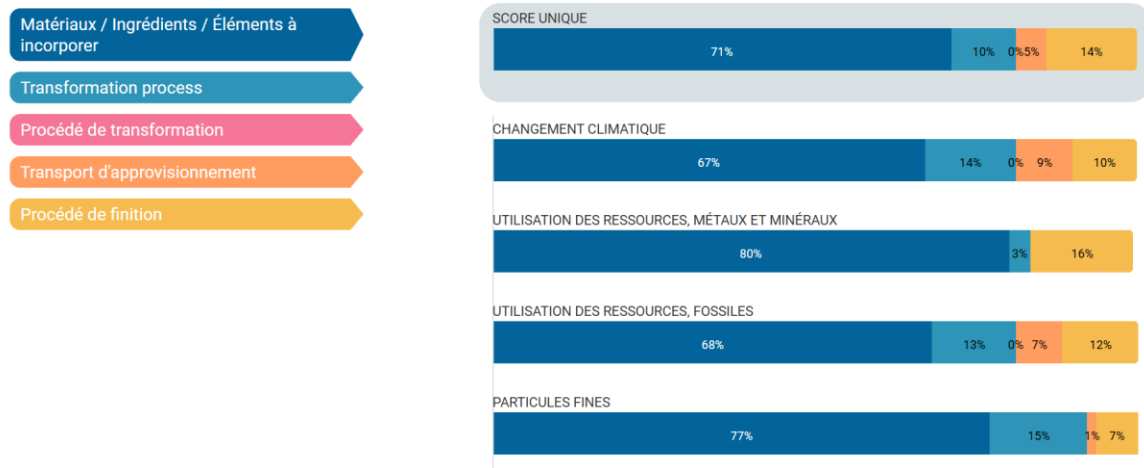


Figure 10. Contribution of materials and life cycle stages to the environmental impacts of the external smartphone battery.

Interpretation

The study therefore makes it possible to quickly identify opportunities for environmental improvement. In this case, the customized aluminum cover could be optimized by considering materials with lower environmental impacts. More generally, the overall environmental performance of the product would also benefit from the reuse of its components as part of a product refurbishment approach. Finally, the study presented here is centered on the product itself, but the software makes it possible to go further by defining a complete life cycle assessment (LCA), integrating the product, its packaging, transport, and end-of-life treatment.

5.2 Use Case 2 – Composite GFRP Leaf Spring

Scope and method

The use case considered in this section is a composite glass fiber reinforced polymer (GFRP) leaf spring manufactured using a resin transfer moulding (RTM) process (Fig. 11). The objective of the study is to model the manufacturing process chain and evaluate both environmental and economic performance using OPLYSIS-eco.



Figure 11. Composite GFRP leaf spring evaluated using the OPLYSIS-eco process-oriented assessment tool.

The process chain includes several manufacturing stages such as cutting, preforming, resin transfer moulding, milling/drilling, handling operations, and tempering. The process model is structured according to the OPLYSIS-eco hierarchy consisting of process chains, processes, process steps, and resources.

In OPLYSIS-eco, CO₂ emissions are determined using an internal calculation approach. The calculation is based on the individual inputs associated with the manufacturing process. These inputs are weighted according to their respective contribution to the CO₂ emissions and subsequently summed to obtain the overall CO₂ value. In addition, material losses, such as material offcuts and production scrap, are taken into account in the calculation.

Unlike LCA tools that explicitly apply established impact assessment methods, such as EF 3.1, ReCiPe, or EN 15804+A2, the CO₂ calculation approach implemented in OPLYSIS-eco is described by the tool provider as an internal calculation. Therefore, based on the information provided by the OPLYSIS-eco contact person, no specific established LCA impact assessment method can be assigned to the CO₂ calculation in OPLYSIS-eco.

Inventory Analysis (LCI)

The assessment is based on generic process assumptions used for benchmarking and comparison of CO₂ calculation tools. The material inventory includes glass fiber and PUR resin, considering both net consumption and production waste rates. The main assumptions used in the model are summarized below:

- Glass fiber:
 - Net consumption: 4.6 kg
 - Additional waste: 10%
 - Carbon footprint: 2.14 kg CO₂/kg

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- PUR resin:
 - Net consumption: 2 kg
 - Additional waste: 5%
 - Carbon footprint: 3.53 kg CO₂/kg

The composite leaf spring has approximate dimensions of 1500 mm length, 90 mm width, and 20 mm thickness.

The manufacturing workflow implemented in OPLYSIS-eco includes the following process steps:

- PS1.1: Cutting
- PS1.2: Preforming
- PS2.1: Preform insertion
- PS2.2: Dosing
- PS2.3: Impregnation and consolidation
- PS2.4: Part extraction
- PS3.1: Handling to milling/drilling
- PS3.2: Milling/drilling
- PS4.1: Handling to tempering
- PS4.2: Tempering

Impact Assessment (LCIA)

The OPLYSIS-eco assessment calculates the carbon footprint of the defined manufacturing chain together with material, operating and investment costs and throughput time. Results can be analyzed by process, process step and resource to identify the operations and material inputs that contribute most strongly to environmental and economic performance. Because the tool applies an internal CO₂ calculation rather than a published LCIA method, the results are used primarily for internal benchmarking, hotspot identification and comparison of manufacturing scenarios.

Interpretation

The OPLYSIS-eco model enables simultaneous calculation of material costs, operating costs, investment costs, throughput time, and environmental impacts such as carbon footprint at different levels of detail. This allows the identification of environmental and economic hotspots within the manufacturing process chain.

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Overall, the study demonstrates how process-oriented eco-efficiency tools can support the evaluation and optimization of composite manufacturing systems by integrating environmental and economic assessments within a single modelling environment.

5.3 Use Case 3 – Recycled Carbon-Fibre Plate with T-Stiffener

Scope and method

A screening study was conducted for internal project evaluation, focusing on one composite piece a plate with T-stiffener using recycled carbon fiber prepreg.

- **Scenarios:** Direct reuse of post-production prepreg waste to make a piece of recycled carbon fiber plate with T-stiffener using SQRTM (Figure 12)

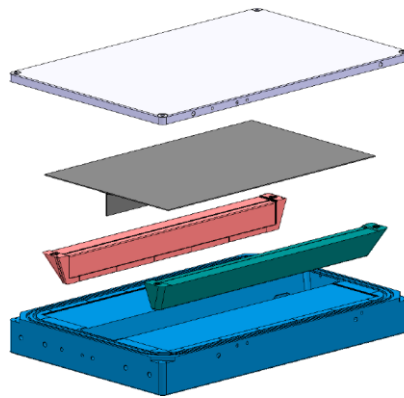


Figure 12. Recycled carbon-fibre composite plate with T-stiffener manufactured from prepreg waste.

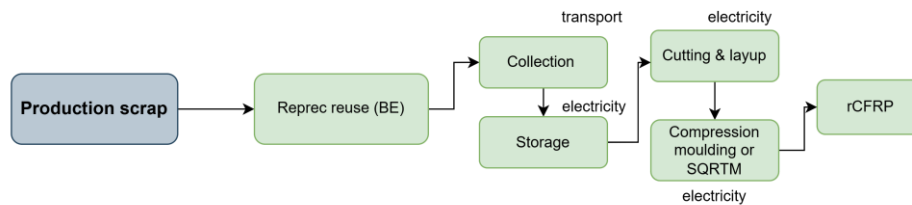
- **Functional unit:** 1 kg of recycled carbon fiber composite product
- **System boundaries:** Cradle-to-gate
- **Allocation rules:** Cut-off (burden stays with the first life, recycled material enters second life with no upstream burden)
- **Impact categories & method:** For the CF recycling sector, Climate change was considered an essential LCA indicator. The life cycle impact assessment was performed for **Climate change** and **Resource use** using the characterization method of the environmental footprint EF3.1 (adapted) implemented in Simapro 10.3 with database ecoinvent 3.11.
- **Data collection:**
 - Foreground (SQRTM fabrication)
 - Background (Ecoinvent database, literature database)

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Inventory Analysis (LCI)

Figures 13 present the process flowchart and life cycle inventory, including the material and energy inputs and outputs.

Flowchart:



Inputs & Outputs:

Input	Terms	Amount	Unit	Used data process
Materials Processing SQRTM	resin	0.748	kg	Epoxy resin, liquid {RER} market for epoxy resin, liquid Cut-off, S
	Mould prepara release agent	0.015	kg	Solvent, organic {GLO} market for solvent, organic Cut-off, S
	Ply-cutting	0.953	kwh	Electricity, medium voltage {BE} electricity voltage transformation from high to medium voltage Cut-off, S
	Lay-up	0.089	kwh	Electricity, medium voltage {BE} electricity voltage transformation from high to medium voltage Cut-off, S
	hot compaction e	2.343	kwh	Electricity, medium voltage {BE} electricity voltage transformation from high to medium voltage Cut-off, S
	Injection + curi	30.238	kwh	Electricity, medium voltage {BE} electricity voltage transformation from high to medium voltage Cut-off, S
	Refrigerated s	6	kwh	Electricity, medium voltage {BE} electricity voltage transformation from high to medium voltage Cut-off, S
	Transport	100	kgkm	Transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, diesel, EURO 5, CO2, liq. ref., freezing {GLO} Cut-off, S
	rCFRP	1	kg	
Output				

Figure 13. Flowchart and inventory analysis for manufacturing the recycled carbon-fibre plate with T-stiffener using SQRTM and

Impact Assessment (LCIA)

The impact assessment shows that the overall environmental profile is mainly dominated by fossil resource use, indicating that fossil-based energy and materials are the principal contributors (in Fig. 14 and Fig. 15). Other relevant categories include ecotoxicity and climate change, whereas water use and human toxicity, non-cancer effects, make comparatively smaller contributions. Based on the study objective and supporting literature, the detailed assessment therefore focuses on climate change and fossil resource use. The results clearly show that the recycled prepreg piece exhibits substantially lower overall impacts. In this case, the

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environmental burden is mainly associated with the fabrication processing step and epoxy resin use, while the absence of virgin carbon fiber production significantly reduces both climate change impact and fossil resource consumption. These results show the environmental benefits of recycling approaches.

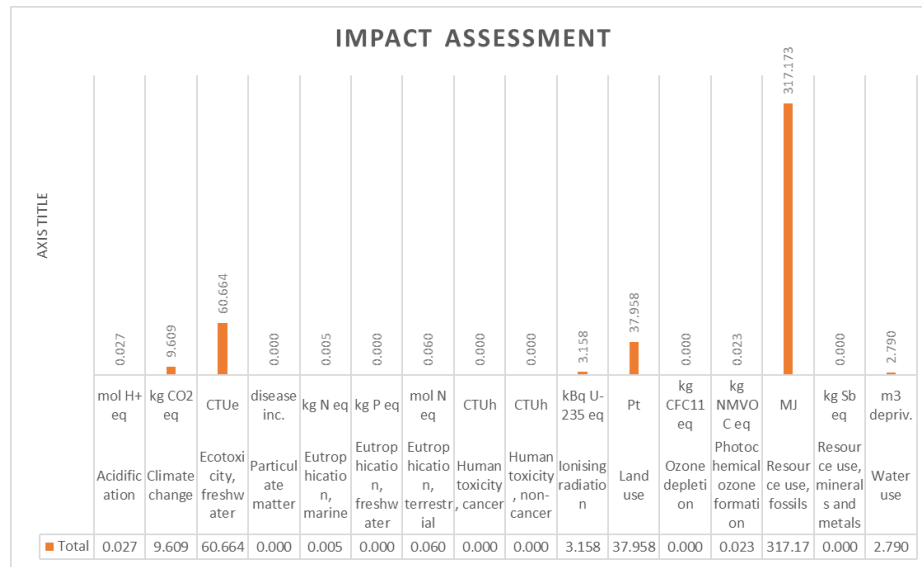


Figure 14. Relative contribution of impact categories to the environmental profile of the recycled carbon-fibre composite product.

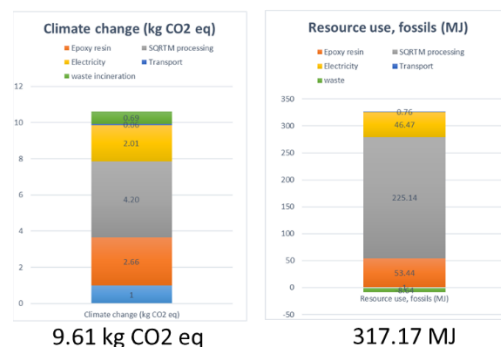


Figure 15. Climate change and fossil resource use comparison between virgin and recycled carbon-fibre composite production scenarios.

Sensitivity analysis

A sensitivity analysis is performed to evaluate storage duration on climate change impact and fossil resource use. As presented in Fig. 16, the results show that storage duration has a more noticeable influence on the results. As the number of storage days increases, both climate change impact and fossil resource use gradually rise. This

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trend suggests that prolonged storage contributes to additional environmental burdens, likely due to associated energy use or logistics requirements.

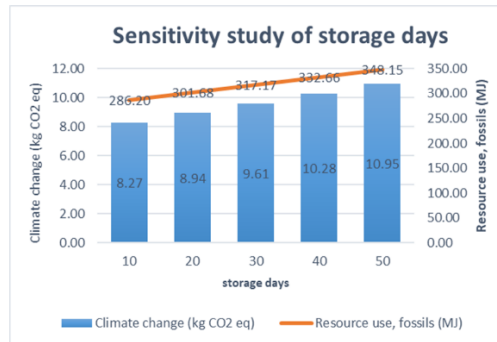


Figure 16. Sensitivity analysis of storage duration on climate change impact and fossil resource use.

Interpretation

The LCA results highlight that carbon fibre production is the dominant contributor to climate change and fossil resource use. Recycling and reuse scenario significantly reduce these impacts by avoiding virgin fibre production. The results confirm that the reuse and recycling of prepreg waste represent promising strategies for improving material circularity in composite applications. However, further optimization and understanding of aging behavior will be essential.

5.4 Use Case 4 – Mono-Material PET Carpets

This case presents a more advanced LCA application. It uses the European Commission's Product Environmental Footprint (PEF) framework and Circular Footprint Formula (CFF) to assess environmental performance to compare the different allocation methods.

Scope and method

The purpose of this study is to apply and evaluate the Circular Footprint Formula (CFF), as part of the European Commission's Product Environmental Footprint (PEF) framework, through an assessment of the environmental performance of thermomechanically recycled mono-material polyester carpets [11]. The environmental assessment is structured around the CFF as the recycling allocation method. In addition, a comparison is made with the 100:0 approach as a benchmark, also known as the cut-off or recycled content method, as recommended in the Environmental Product Declaration (EPD).

Both allocation methods were applied to the carpet case study, which considered three possible scenarios: recycling of the mono-material carpet (MMC) (Product system 1, flowchart in Fig. 17), incineration of the conventional multi-material carpet (Product system 2, flowchart in Fig. 18), and incineration of the MMC (Product system

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3, flowchart in Fig. 19)). The impact assessment follows the indicators defined by the PEF framework. All the detailed information can be found in article [11].

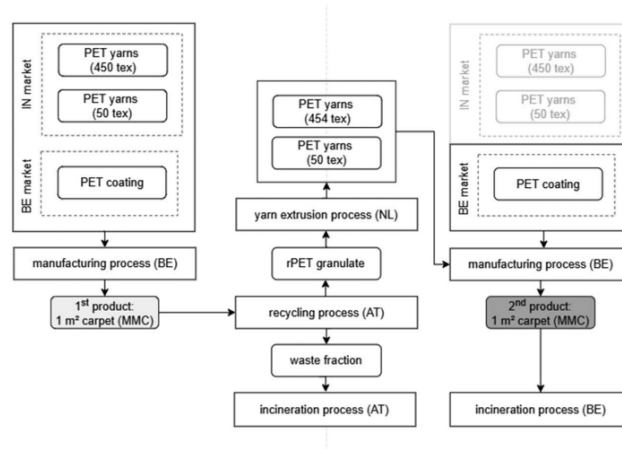


Figure 17. Product System 1: mono-material PET carpet with thermomechanical recycling.

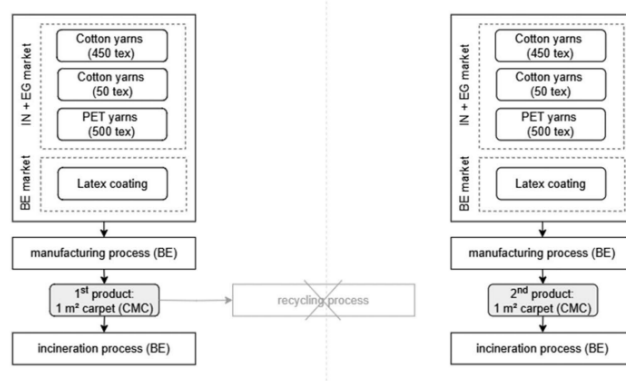


Figure 18. Product System 2: conventional multi-material carpet with incineration and energy recovery.

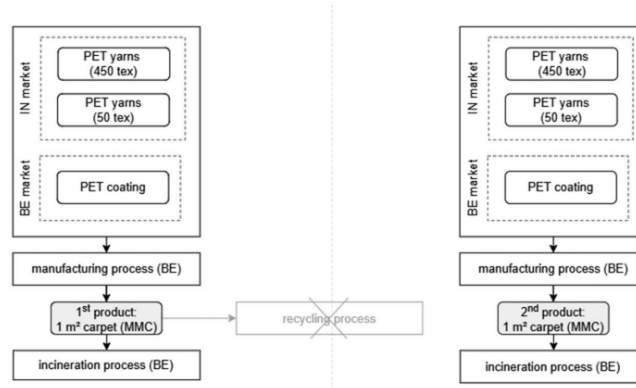


Figure 19. Product System 3: mono-material PET carpet with incineration and energy recovery.

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Inventory Analysis (LCI)

The inventory covers the material and energy flows associated with carpet production and the selected end-of-life routes for the three product systems. It includes the mono-material PET carpet and the conventional multi-material carpet, thermomechanical recycling operations, incineration with energy recovery, transport and the production of substituted virgin materials. All flows are related to the study's functional basis of 1 m² of carpet, while the modelled product systems correspond to 2 m². Life cycle inventory boundaries and principal flows considered for the three carpet product systems are shown below.

E	Inventory flow	MMC	CMC	unit	Ecoivent dataset
E_v	PET yarns 450 tex	1.12	-	kg	Polyester fiber production, finished {IN} - modified
	PET yarns 50 tex	0.11	-	kg	Polyester fiber production, finished {IN} - modified
	PET yarns 500 tex	-	0.22	kg	Polyester fiber production, finished {IN} - modified
	CO 450 tex	-	0.90	kg	See Supplementary Information
	CO 50 tex	-	0.11	kg	See Supplementary Information
	PET resin	0.20	-	kg	Market for PET, granulate, amorphous {GLO}
	Latex	-	0.11	kg	Market for latex {RER}
	Polyacrylic comp.	0.10	0.01	kg	Acrylic dispersion, in 58% solution state {RER}
	Surfactant	0.01	0.01	kg	Market for non-ionic surfactant {GLO}
	CaCO ₃ filler	-	0.19	kg	Market for calcium carbonate, precipitated {RER}
E_R	Demi water	0.68	0.07	kg	Market for water, deionised {Europe excl. CH}
	Wastewater	7E-04	7E-05	m ³	Treatment of wastewater, average {Europe excl. CH}
	SSP process	0.47	-	kwh	Market for electricity, medium voltage {AT}
E_D	Extrusion process	1.24	-	kg	Polyester fiber production, finished {IN} - modified
	Municipal incineration	1.50	1.50	kg	Treatment of municipal solid waste, incineration {BE}
E_{SE}	Plastics incineration	0.23	-	kg	Waste plastic, mixture, incineration {Europe excl. CH}
	Electricity	1.50	1.50	kwh	Market for electricity, medium voltage {BE}
	Heat	1.50	1.50	MJ	Market for heat, central/small-scale, natural gas {RER}

Impact Assessment (LCIA)

The LCIA compares climate change impacts and the PEF single score per square metre of carpet for the three product systems. The analysis also evaluates how the CFF parameters A and B and the alternative cut-off allocation approach influence the ranking of recycling and incineration scenarios (In Fig. 20).

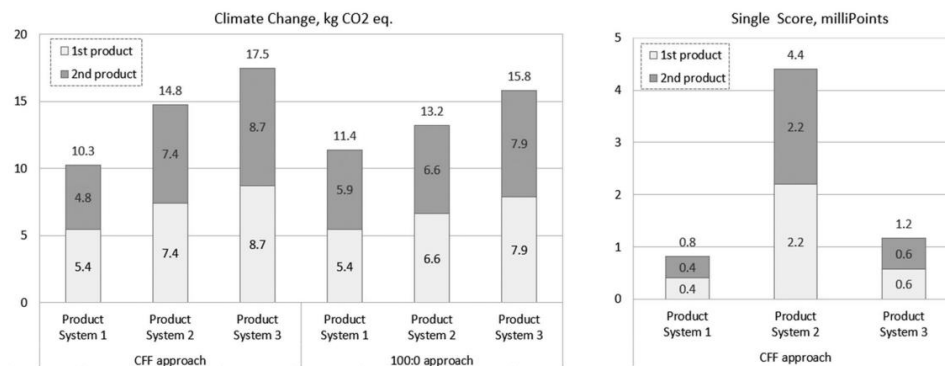


Figure 20. Climate change and PEF single-score comparison of the recycling and incineration scenarios for the carpet product systems.

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Interpretation

In the evaluation of each Product System, the Climate Change impact assessment indicates that recycling of a MMC (Product System 1) is more beneficial than direct incineration of a CMC or an MMC without recycling (Product Systems 2 and 3). This conclusion is consistent with the principles of the circular economy. The result is further supported by the single score impact, which aggregates all individual impact categories into a single value. However, the single score is associated with a high level of uncertainty (with probabilities of close to 50%). Similarly, high uncertainties of around 50% are observed for ecotoxicity, human toxicity, ozone formation, and water use. In addition, there are specific impact categories for which the recycling scenario results in higher impacts with a high probability, such as ozone depletion and fossil resource use.

References

[11] Huysman, S., Yin, J., & Hammar, T. (2026). Evaluating the Circular Footprint Formula (CFF) in the environmental assessment of mono-material carpets recycling: A case study approach. *The International Journal of Life Cycle Assessment*, 31, 44. <https://doi.org/10.1007/s11367-026-02619-y>

Chapter 6: Future Trends

This chapter provides an overview of emerging trends relevant to Life Cycle Assessment (LCA) and Eco-Design in the composites sector. These trends are based on ongoing industrial developments, recent research activities, and evolving regulatory and market contexts.

The objective is not to be exhaustive, but to highlight topics that are expected to have an increasing influence on material selection, product design, manufacturing choices, and environmental assessment practices in the coming years.

The trends presented in this chapter are particularly relevant for small and medium-sized enterprises (SMEs), as they may progressively impact customer requirements, sustainability strategies, and the practical use of LCA and Eco-Design tools.

The following sections focus on:

- Bio-based and alternative composite materials,
- recycling technologies and circular economy approaches,
- digitalization and the use of advanced tools for LCA,
- policy and regulatory developments.

6.1 Bio-based and low impact Composites

The development of bio-based and renewable composite materials is one of the most prominent trends in sustainable material innovation. This includes natural fibers (e.g. Flax, hemp), bio-based or partially bio-based resins and hybrid material solutions.

Life Cycle Assessment studies show that bio-based composites can reduce reliance on fossil resources and lower greenhouse gas emissions during material production. However, the results strongly depend on agricultural practices, processing routes, durability and end-of-life scenarios [20,21].

For SMEs, LCA is a key tool to objectively compare bio-based and conventional composite solutions, avoiding simplistic assumptions and supporting informed eco-design decisions.

6.2 Recycling Technologies

Recycling remains a major challenge for fibre-reinforced composites, particularly thermoset systems used in aerospace, automotive, construction and wind-energy applications. Their cross-linked matrices cannot be remelted, and the strong adhesion between fibres and resin makes material separation difficult. Recycling strategies must therefore be selected according to the composite type, waste condition, required quality of the recovered material, processing energy and targeted second-life application.

Mechanical recycling uses cutting, shredding, milling and classification to convert composite waste into flakes, fibres or powder. It is comparatively simple and mature and generally requires less energy than thermal or chemical routes. However, it shortens the fibres, reduces reinforcement performance and produces heterogeneous recyclates that are mainly suited to fillers, short-fibre compounds, cement products or other lower-demand applications.

Thermal recycling, particularly pyrolysis, decomposes the polymer matrix in an oxygen-limited environment and can recover fibres while generating gaseous and liquid by-products. This route is especially relevant for carbon-fibre composites because recovered fibres can retain useful properties and substitute part of the demand for energy-intensive virgin fibres. Its environmental performance nevertheless depends on process temperature, energy source, fibre cleaning, recovery yield and the value assigned to co-products.

Chemical recycling, including solvolysis, uses solvents—often combined with heat, pressure or catalysts—to break down the matrix and recover fibres with limited mechanical damage. It may also enable recovery of resin-derived compounds. Although it offers high-value recovery potential, further development is needed to control solvent consumption, treatment conditions, purification requirements, scalability and operating costs.

Life Cycle Assessment is essential for comparing these routes because recycling does not automatically provide an environmental benefit. The assessment should include collection and transport, waste preparation, energy and auxiliary materials, emissions, recovery yield,

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quality loss, residue treatment and the extent to which the recovered material substitutes virgin production. Recent wind-blade studies illustrate this need: using blade waste as cement-clinker feedstock can reduce global-warming and respiratory-health impacts relative to virgin feedstock, whereas use in fibreglass production can involve trade-offs [22]. Comparative assessment also indicates that recyclable thermoplastic blade designs can substantially reduce impacts relative to conventional epoxy-GFRP solutions [23].

For SMEs, the most appropriate route should therefore be selected by combining environmental results with technical quality, market demand, production volume and economic feasibility. In practice, mechanical recycling may provide an accessible option for clean production scrap, while pyrolysis or solvolysis may be justified when preserving fibre value or recovering chemical fractions is critical. Design-for-disassembly, mono-material concepts, traceability and improved sorting can further increase recovery efficiency and the quality of secondary materials.

6.3 Digitalization and AI in LCA

Digitalization is transforming how environmental assessment are performed and integrated into product development. Key trends include automate data collection, integration of LCA into CAD and PLM systems and the use of artificial intelligence to accelerate assessments.

Recent research shows that combining LCA with machine-learning models can support sustainability-driven design decisions for composite structures and advanced materials by linking environmental indicators with performance optimization [24,25].

For SMEs, simplified and digital LCA tools represent an accessible step toward design integrated life cycle thinking, even without advanced digital infrastructure.

Digital technologies are transforming the way Life Cycle Assessment (LCA) is performed. Although LCA remains the reference methodology for evaluating environmental impacts, its broader adoption is constrained by time-consuming data collection, incomplete inventories, static models and the need for specialized expertise. Artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), big data and blockchain therefore offer opportunities to improve LCA efficiency and data quality while preserving the methodological principles of ISO 14040/44 [26].

AI is currently applied mainly to LCI development, where machine-learning algorithms can automate data extraction and classification, identify appropriate datasets, estimate missing values and develop surrogate models. Supervised learning is currently the most common approach, particularly for data collection and inventory analysis [27]. Generative AI and large language models could further support the extraction of information from technical documentation, stakeholder mapping, process descriptions and preliminary system-boundary definition. However, expert verification remains essential because outputs may be incomplete or inaccurate.

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A concrete example of this evolution is the EU-funded **ECOPILOT** project, which is developing an AI-enabled conversational Product Environmental Footprint (PEF) Copilot for the furniture and mattress sectors. The tool is designed to guide SMEs and innovators through environmental assessments and eco-design decisions by combining LCA, Safe and Sustainable by Design principles, circularity modelling and AI-assisted data support. Its planned functions include proxy dataset recommendations for incomplete inventories, prospective datasets for emerging materials, uncertainty analysis, circularity and end-of-life scenario modelling, and compliance-ready outputs. Industrial validation focuses on safer alternatives for adhesives, flame retardants and polyurethane coatings, while considering environmental performance, circularity and practical implementation [28].

Recent research goes one step further towards agentic LCA, in which AI agents coordinate several tasks of an assessment. Approaches combining AI agents with integrated assessment models suggest that activities across the four LCA phases could progressively be automated [29]. A recent application to electronic products demonstrated the potential of AI agents to autonomously generate life cycle inventories, illustrating how such systems could accelerate assessments while still requiring validation across products and impact categories [30].

Digitalization also enables more dynamic and representative LCA models. IoT sensors can automatically collect primary operational data from production equipment, transport systems and products, replacing generic assumptions with more granular information. One study reviewed by Popowicz et al., for example, found that a generic model overestimated machine energy consumption by approximately 74% compared with direct sensor measurements. Combined with predictive models, such data can support prospective LCA and eco-design by evaluating alternative materials, process parameters or supply-chain configurations before implementation. This evolution towards more connected and continuously updated environmental models is also highlighted in current developments around LCA software and data infrastructures (SimaPro, *Data innovation drives transformation in sustainability; SimaPro in 2030: where are we headed?*).

The greatest benefits may arise from combining digital technologies. IoT can provide primary data; blockchain can strengthen data exchange, reliability and traceability; big-data infrastructures can manage large and heterogeneous datasets; and AI can analyse these data to estimate missing inventories, predict LCA results and identify environmental hotspots. AI can also support Life Cycle Impact Assessment (LCIA) and interpretation by estimating missing characterization factors, identifying influential variables, supporting uncertainty analysis and exploring alternative scenarios.

Nevertheless, digitalization does not remove the need for methodological expertise. AI results remain dependent on the quality, completeness and representativeness of the underlying data, while algorithms introduce additional issues concerning transparency, reproducibility and explainability. A promising approach is therefore hybrid intelligence, in which AI performs repetitive and data-intensive tasks while LCA and domain experts retain

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responsibility for system boundaries, data selection, assumptions, validation and interpretation [27].

Finally, the environmental footprint of AI itself must be considered. Its impacts extend beyond electricity consumption during model training to hardware production, data storage, inference, networks and end-user devices. A comprehensive assessment should therefore consider the complete life cycle of AI infrastructure and multiple environmental indicators rather than carbon emissions alone [31].

Overall, digitalization is progressively transforming LCA from a largely static and labour-intensive exercise into a more connected, data-driven and decision-oriented methodology. AI, IoT, big data and blockchain can improve data collection, traceability, modelling and scenario analysis, while emerging AI agents may enable substantially greater automation. Their most credible role, however, remains to augment rather than replace LCA expertise, combining automation with human judgement to improve both efficiency and scientific robustness.

6.4 Policy and Regulatory Developments

Environmental policies increasingly require transparency regarding product level environmental impacts, including carbon footprint reporting and circularity aspects.

In sectors such as automotive and construction, LCA is becoming a reference methodology for regulatory compliance and customer requirements, supported by international harmonization initiatives. The UNECE automotive LCA working group is developing a coherent procedure to improve the comparability of vehicle life cycle assessments [32].

Although regulations often target large companies first, SMEs are progressively impacted through supply-chain requirements, making early adoption of LCA a strategic advantage.

6.5 Strategic Outlook for Advanced materials SMEs

Rather than viewing sustainability as a constraint, composite SMEs can leverage LCA and Eco-Design as innovation and decision support tools.

Key strategic lessons emerging from recent studies and industrial experience include:

- Starting with simplified LCA approaches
- Using LCA to identify environmental hotspots
- Integrating sustainability early in product development
- Progressively building internal competence.

Overall, life cycle thinking combined with accessible tools enables SMEs to move from reactive compliance towards proactive sustainability strategies. Integrated LCA and life cycle costing can support material and product decisions in composite applications, while

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prospective LCA can incorporate future changes in materials, energy systems and manufacturing conditions during product development [33,34].

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Appendices

Templates for Official LCA Declaration Reporting

The following template can be used to prepare a draft Environmental Product Declaration (EPD) for an office product. It is a working template only: the final declaration must follow the latest requirements of the selected programme operator, the applicable Product Category Rules (PCR) and any complementary PCR. The final EPD must be independently verified before publication.

Template – Environmental Product Declaration for an Office Product

Declaration field	Information to complete
EPD title	[Environmental Product Declaration for product name and model]
EPD owner	[Legal company name, address, website and contact]
Product	[Office chair / desk / table / storage unit / workstation component]
Manufacturer	[Manufacturing company and production site(s)]
Programme	[Programme operator and website]
Registration number	[Assigned by programme operator]

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Type of EPD	[Single product / average product / multiple products / worst-case]
PCR and c-PCR	[PCR title, registration number, version and validity date; complementary PCR for furniture if applicable]
Product classification	[UN CPC, CPV or other applicable classification]
Standards	[ISO 14025; ISO 14040/14044; EN 15804+A2 where applicable; relevant furniture standards]
Publication and validity	[Publication date, version date and validity date]

1. General Information and Verification

- **Programme information:** [Programme operator, address, website and contact].
- **PCR review:** [PCR review body, chair and contact].
- **LCA responsibility:** [Name, organisation and contact of LCA practitioner].
- **Independent verification:** [Individual verification / accredited certification body / other approved route].
- **Third-party verifier:** [Name, organisation, contact and approval body].
- **Follow-up during validity:** [Describe procedure for monitoring significant changes in materials, energy, suppliers, production or product design].
- **Responsibility statement:** The EPD owner has sole ownership, liability and responsibility for this declaration.
- **Comparability statement:** EPDs are comparable only when they are based on equivalent PCRs, functional or declared units, system boundaries, data-quality requirements, allocation rules and impact-assessment methods.

2. Company and Product Information

- **Organisation description:** [Main activities, production sites, quality and environmental certifications].
- **Product name and model:** [Commercial designation and product family].
- **Product description:** [Function, main components, intended use, dimensions, mass and variants covered].
- **Technical performance:** [Load capacity, durability, fire performance, ergonomics, resistance, applicable office-furniture standards and warranty].
- **Geographical scope:** [Production location and market area].
- **Product image:** [Insert representative image].
- **Additional environmental information:** [Repairability, replaceable parts, recycled content, take-back scheme, disassembly and recyclability claims].

3. Declared or Functional Unit

Parameter	Value
Declared/functional unit	[Example: one office chair providing seating for one user over the reference service life defined by the applicable PCR]

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Product mass	[kg per declared unit]
Reference service life	[years, where required]
Conversion factor	[Factor needed to convert reported results to another relevant unit]

4. Content Declaration

Component/material	Mass (kg)	Share (%)	Recycled content (%)	Technical function
[Steel or aluminium frame]				[Structural support]
[Polymer components]				[Shell, mechanisms or accessories]
[Foam, textile, leather or upholstery]				[Comfort and surface finish]
[Wood or wood-based panels]				[Desktop, seat, backrest or storage]
[Electronic/electrical parts]				[Height adjustment, controls or connectivity]
[Packaging]				[Product protection and distribution]

Hazardous substances and biogenic carbon: [Report regulated substances, candidate-list substances, certification schemes and biogenic carbon content where required by the PCR].

5. LCA Information

- **Goal:** [Purpose of the EPD and intended audience].
- **System boundary:** [Cradle-to-gate / cradle-to-grave / other system boundary required by the PCR].
- **Life cycle stages:** [Raw-material supply, transport, manufacturing, distribution, installation, use, maintenance, repair, replacement, end-of-life and benefits beyond the system boundary, as applicable].
- **Cut-off criteria:** [Rules applied and excluded flows].
- **Allocation:** [Mass, economic, physical, recycled-content, CFF or other applicable approach].
- **Data period:** [Reference year and period covered by primary data].
- **Primary data:** [Manufacturing sites, energy, materials, water, waste and emissions].
- **Background data:** [Databases, versions and geographical representativeness].
- **Electricity modelling:** [Supplier-specific, residual mix, national mix or other documented approach].
- **LCIA method:** [Method and characterization-factor version required by the PCR].
- **Software:** [Software name and version].

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- **Data quality:** [Technological, temporal and geographical representativeness; completeness and uncertainty].
- **Assumptions and limitations:** [Key scenarios, proxies and exclusions].

6. Life Cycle Modules and Scenarios

Stage/module	Scenario and assumptions	Declared
Raw materials and manufacturing	[Material production, supplier transport, manufacturing yields, assembly and packaging]	[Yes/No]
Distribution	[Transport mode, distance, load factor and market]	[Yes/No]
Installation	[Assembly energy, ancillary materials and packaging waste]	[Yes/No]
Use and maintenance	[Cleaning, maintenance, repair, replacement and electricity where relevant]	[Yes/No]
End-of-life	[Collection, dismantling, reuse, recycling, incineration and landfill rates]	[Yes/No]
Benefits beyond system boundary	[Credits from reuse, recycling or energy recovery, where allowed]	[Yes/No]

7. Environmental Performance Results

Indicator	Unit	Production	Distribution/use	End-of-life	Beyond system boundary
Climate change - total	kg CO ₂ eq				
Ozone depletion	kg CFC-11 eq				
Acidification	mol H ⁺ eq				
Eutrophication	[Applicable unit]				
Photochemical ozone formation	kg NMVOC eq				
Resource use - minerals and metals	kg Sb eq				
Resource use - fossils	MJ				
Water use	m ³ world eq deprived				

Add the complete sets of mandatory resource-use, waste-category and output-flow indicators required by the applicable PCR and programme operator. Report values using the prescribed modules, units, decimal format and indicator names.

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8. Interpretation and Additional Information

- **Environmental hotspots**
- **Sensitivity and uncertainty**
- **Improvement actions**
- **Circularity information**
- **References**
- **Contact**

Final control before publication: confirm that the latest programme template and applicable PCR versions have been used; all mandatory indicators and modules are complete; datasets and assumptions are traceable; product claims are consistent with the verified LCA; and the declaration, supporting report and machine-readable data have passed independent third-party verification.