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Project SustDesignTex (GA No. 101079009), title: „Sustainable Industrial Design of Textile Structures for Composites" funded by the European Union

DELIVERABLE REPORT

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Deliverable Title	**D.4.1. *(Methodical Recommendations on Life Cycle Assessment application for innovative composites evaluation)***
Deliverable Lead:	*University of Zaragoza (UNIZAR)*
Related Work Package:	*WP4: Sustainable development aspects in production of innovative Textile Reinforcement Composites: CSA measures*
Related Task(s):	*Task 4.1 Short-term staff exchanges and expert visits for acquaintance with the sustainable development aspects in production of innovative Textile Reinforcement Composites (M23 – M33).*
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Abstract:	*The primary goal of Deliverable 4.1 was to share advanced knowledge in sustainable textile composite production from the University of Zaragoza with researchers at Lodz University of Technology. Under the framework of this work package and deliverable, seven TUL researchers visited the University of Zaragoza for two months, September 2024 to November 2024, for a short-term staff exchange; each researcher stayed in Zaragoza for two months and conducted research under different micro-project titles which are linked to work package four. Two researchers took the lead on LCA, while the others contributed to broader efforts in composite materials and sensor technology.* *As part of this deliverable, an immense knowledge exchange was obtained between the consortium partner universities and this know-how will be also shared to the business and science communities of Lodz University of Technology as part of task 4.2 under the work package 4 in the form of training.*

	By combining the expertise of both universities, the project aims to develop innovative and sustainable textile composite materials that address environmental concerns and contribute to a more sustainable future.

Methodical Recommendations on Life Cycle Assessment application for innovative composites evaluation

1. Life Cycle Assessment Definition

Life Cycle Assessment (LCA) is a methodology used to evaluate the potential environmental impacts and resource consumption associated with a product’s entire lifecycle. This encompasses all stages, from raw material extraction and production to usage and final waste management, including both disposal and recycling. The term "product" refers to both goods and services [1].

LCA provides a holistic evaluation, taking into account all aspects of the natural environment, human health, and resource use. Its distinct characteristic is the life-cycle perspective, which examines a product comprehensively across all phases.

An LCA (Life Cycle Assessment) is structured into four phases: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

The Goal and Scope Definition phase outlines the objectives of the study, its intended applications, and the target audience [1]. This phase also establishes the system boundaries and defines the functional unit, which serves as a quantitative representation of the functions provided by the goods or services under assessment.

In the LCI phase, data is collected to compile inputs (resources consumed) and outputs (emissions generated) throughout the product's life cycle, all quantified relative to the functional unit.

The LCIA phase aims to quantify and evaluate the magnitude and significance of the potential environmental impacts of the system being studied [1].

Finally, the Interpretation phase involves evaluating the findings from all previous phases against the defined goal and scope, leading to conclusions and actionable recommendations [1].

2. LCA general overview and current challenges

LCA is a powerful tool for estimating the energy use and environmental impacts associated with products or services, however, LCA results are not inherently precise, as they are influenced by numerous sources of uncertainty. Although governed by international standards ISO 14040 and ISO 14044, the methodology allows for varying approaches and decisions and the reliability of LCA findings heavily depends on the availability of comprehensive and accurate data, which is often limited [1,2].

ISO 14040 [1] emphasizes the importance of examining parameters that may significantly impact the final results. The Life Cycle Inventory (LCI) results are frequently used for comparative purposes, ensuring high data quality is crucial to validate the findings [3].

Key considerations for data quality in LCA studies include time-related, geographical, technological coverage, data precision, completeness, representativeness, consistency, reproducibility, and clarity regarding data sources and uncertainties.

Moreover, LCA practitioners use different LCA software and databases. As a result, the interpretation phase of the LCA becomes critical for enhancing the study's overall quality. However, challenges related to life-cycle inventory and impact assessment software and databases persist, such as: Significant discrepancies in emission data for the same material or process across different databases; insufficient documentation on the origins and validity of emission data and limited public availability of data;

Additional uncertainty sources include data inaccuracies, data gaps or unrepresentative datasets; definition of system boundaries; characterization factors and weights used in calculating potential environmental impacts between others.

The present report compiles a list of recommendations in order to perform a LCA for sustainable textile for composite materials to ensure transparency and uniformity in LCAs, facilitating reproducibility and comparability of the results. The guidelines provide a structured, comprehensive description of the methodologies to quantifying material- and energy-flows and their associated emissions caused on the basis of the two LCA standards, ISO 14040 and 14044 [1,2].

3. List of Methodical Recommendations

Scope and System boundaries

The scope in an LCA defines the purpose, objectives, and extent of the study. It includes key elements such as the functional unit (a quantitative measure of the function that the product or service provides), the assumptions, limitations, and the type of impacts to be assessed. The scope ensures that the LCA aligns with the intended goals and provides clarity on how the results will be used.

For the realization of an LCA for the textiles for composite materials, the following items should be explicitly and clearly indicated at the beginning of the study:

Goal: Assess the environmental impact of textiles for composite materials, the assessment should be conducted to provide clear comparability between materials.

Functional Unit.

Impact Categories

Assumptions.

Limitations.

System boundaries delineate which processes and life cycle stages are included or excluded in the LCA study. These boundaries determine the extent of the analysis, such as whether to include raw material extraction, transportation, manufacturing, usage, and end-of-life processes like disposal or recycling. Setting clear boundaries ensures consistency and prevents unnecessary inclusions or exclusions that could skew results.

The EU's Product Environmental Footprint (PEF) methodology sets comprehensive standards for LCA system boundaries: "The system boundary shall be defined following a general supply-chain logic, including all stages from raw material acquisition and pre-processing, production of the main product, product distribution and storage, use stage and end of life treatment of the product (if appropriate)."

System Boundaries should be defined according to the following definitions:

1. *Cradle-to-Grave:* Includes all processes from raw material extraction (cradle) to disposal or recycling (grave).

2. *Cradle-to-Gate:* Includes processes from raw material extraction to the point the product leaves the manufacturing site (gate).

3. *Gate-to-Gate:* Focuses on specific production stages or processes, excluding the entire lifecycle.

4. *Cradle-to-Cradle:* Similar to cradle-to-grave, it assumes closed-loop recycling, where the product or its materials re-enter the lifecycle after use.

The objective should be to compare the different textiles used for composite materials, from cradle to grave.

Regarding the geographical limits, if there is no precise location of the production site of the material and of the suppliers of all the components, *Global* processes that include a representative product of a global market will be used by default. In any case, it is essential to declare the location of all the processes selected for the LCA.

For the specific case of energy use in the composite manufacturing process, data from the country of manufacture of the composite should be used, and its electrical mix should be updated at least two years prior to the current date of completion of the LCA. In any case, the source and the mix used must also be specified.

Concerning time limits, the period of time in which the evaluation of each of the processes has been carried out should be indicated, as well as verifying that the selected processes are representative of the current market situation, eliminating obsolete processes.

Functional Unit

The functional unit and the reference flow are defined in the ISO standards as follows:

Functional unit: Quantified performance of a product system for use as a reference unit.

Reference flow: Measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit

The functional unit describes and quantifies the properties of the product. These properties (functionality, appearance, stability, durability, ease of maintenance, etc.) are in turn determined by the requirements in the market in which the product is to be sold [4].

The reference flows translate the abstract functional unit into specific product flows for each of the compared systems, so that product alternatives are compared on an equivalent basis, reflecting the actual consequences of the potential product substitution. The reference flows are the starting points for building the necessary models of the product systems [4].

In the specific case of sustainable textiles for composite materials, the main function is to give consistency, resistance, and protection to the drone itself and the electronic components inside the drone. The composite material must protect it during the whole useful life of the drone.

To compare different materials, these must ensure the described function throughout the life of the product.

Therefore, the functional unit recommended in this case is the coverage of 1 m2 of drone during the years of its useful life.

The physical properties of the material that may impact on the development of its performance with higher or lower quality, they should be declared together with the functional unit. The thermal resistance of the material has been identified as a relevant property and should be declared in the first phase of the LCA.

The reference flow is the quantity (kg) needed to cover 1m2 of the drone.

It is necessary to define the reference flow in the first stage of the LCA since declaring the mass quantities of each product is essential to be able to evaluate the behavior of the product in its end-of-life phase.

Life cycle inventory analysis

The LCI is the "Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle".

Every LCA is built upon Life Cycle Inventory (LCI) models, which outline the material and energy requirements of the product system being analyzed. This chapter discusses the aspects of inventory modeling that must be standardized to ensure the comparability of results. The selection of a system model significantly influences the results of an LCA, making this choice critically important. The appropriate system model should align with the specific goal of the LCA study. Nevertheless, the general recommendation for comparing products or systems is to adopt an attributional approach.

The product system shall be divided into foreground- and background-processes [5] the following definitions are:

− Foreground system: those processes on which measures may be taken concerning their selection or mode of operation as a result of decisions based on the study. The foreground processes are those which the decision-maker or product-owner can influence directly.

− Background processes are all remaining processes of the particular product system.

The LCI data shall be divided into primary and secondary data. The primary data is related to foreground processes, the data is measured, controlled and defined by the product-owner.

Background databases play a crucial role within the life cycle assessment of SHC systems, contributing to the accuracy and the reliability of the assessment. This is related to the secondary data coming from processes defined in the LCA databases.

The used databases have to be clearly stated, with full transparency of the documentation and availability of the unit process information and data. However, these methodology recommendations report do not recommend the use of particular background database but strongly encourages not to mix data from different databases whenever possible. The suitability of all secondary data should also be declared.

LCA methods and impact categories selection

The LCIA is the “Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product”. There are mandatory and optional elements in the LCIA phase.

The *mandatory* elements include:

i) the selection of relevant environmental impact categories (*selection*)

ii) the assignment of LCI results to the selected impact categories (*classification*),

iii) the calculation of environmental impact scores (*characterization*).

the *optional* elements consist of:

i) Normalization: it is a comparison of the magnitude of the potential impacts with the reference values in a geographic area over a given period of time (*normalization*),

ii) Grouping or ranking impact indicators (*grouping*), and

iii) Weighting: aggregation of environmental impacts (*weighting*).

There are different relevant impact assessment methods, the most widespread are the following:

- **CML IA**: Developed by Leiden University (2001). Methodology based on midpoint indicators (problem-oriented approach). The impact categories included are: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (OLDP) and photochemical oxidation potential (PCOP).

- **ReCiPe 2016**: The primary objective of the ReCiPe method is to transform the long list of life cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category: 18 midpoint indicators and 3 endpoint indicators. The midpoint indicators are: Climate Change (CC, kg CO2 eq.), Ozone Depletion Potential (ODP, kg CFC-11 eq.), Terrestrial Acidification Potential (TAP, kg SO2 eq.), Freshwater Eutrophication Potential (FEP, kg P eq.), Marine Eutrophication Potential (MEP, kg N eq.), Human Toxicity Potential (HTP, kg 1,4-DB eq.), Photochemical Oxidant Formation Potential (PCOP, kg NMVOC), Water Depletion Potential (WDP, m3), Metal Depletion Potential (MDP, kg Fe eq.) and Fossil Depletion Potential (FDP, kg oil eq.).

- **IPCC 2021**: Developed by the Intergovernmental Panel on Climate Change. Factors are expressed as Global Warming Potential over the time horizon of different years, being the most common 100 years (GWP100), measured in the reference unit, kg CO2 equivalent.

- **Cumulative Energy Demand (CED)**: This indicator is introduced to represent the extraction and utilization of total primary energy used to produce a process or product from nature, summing the energy of all resources required. The CED analyzes the total amount of energy demanded by a product. The Characterization factors are given for energy resources divided into 2 impact categories: Non-renewable and Renewables resources.

For the objective of the project, it would be recommended to include at least the following impact categories:

- GWP (IPCC): is the most widespread impact category and the easiest to understand when communicating environmental information. In addition, the composite includes natural material, in which the amount of biogenic carbon can be analysed.
- Land Use (RECiPe): Because they are natural fibres, the intensity of land use for their cultivation is relevant for determining their sustainability.
- Eutrophication (RECiPe): Because they are natural fibres, the use of fertilisers and nutrients for their cultivation is relevant to determine their sustainability, as they generate this process.
- Acidification (RECiPe): Because they are natural fibres, the use of fertilisers and nutrients for their cultivation is relevant to determine their sustainability, as they generate this process.
- Water Use (RECiPe): Because they are natural fibres, the intensity of water use for their cultivation is relevant for determining their sustainability.
- CED: due to the energy requirements for the manufacture and recovery of composites.

The End of Life (EoL)

The End-of-Life (EoL) is the last life-cycle stage in LCA (the "grave"), it is necessary to consider what happens to the product once it is discarded, and how to account for recycled materials' environmental benefits.

The product enters EoL when it is either Processed as waste, generally incinerated or landfilled, sometimes composted or left standing. Or Recycled or reused in another product.

The task is 1) to map the product system, finding out what scenario applies to which part of the product. And 2) to model these processes in the LCA software by linking them to environmental data.

As composites, they will have specific material recovery and recycling scenarios that may limit their circularity. A detailed and specific analysis of the recovery and recycling of this type of materials would be necessary, as they need thermal energy to be recovered. This end-of-life process may have relevant energy and environmental burdens.

Result Interpretation

The interpretation phase is essential for extracting meaningful insights and guiding decision-making to improve the environmental performance of a product. In this final stage, the results of the life cycle inventory and impact assessment are systematically evaluated to identify key environmental hotspots, assess trade-offs, and ensure the reliability of conclusions. For projects involving natural fiber composites, it is important to consider factors such as energy consumption during fiber processing, biodegradability of materials, and end-of-life scenarios. Sensitivity analyses should be conducted to test the robustness of the results. Additionally, comparative assessments can help determine whether natural fiber composites outperform conventional alternatives in terms of sustainability. Lastly, the interpretation should align with the project objectives and recommend strategies for optimization, ensuring that the conclusions are clear and consistent with the intended environmental goals.

With respect the sensitivity analysis, its aim is to identify and focus on key data and assumptions that have most influence on a result. It can be used to simplify data collection and analysis without compromising the robustness of a result or to identify crucial data that must be thoroughly investigated.

Sensitivity analysis involves systematically varying each parameter within a plausible range, such as between known maximum and minimum values, or by applying a geometric factor (e.g., doubling or halving the parameter). The results are then examined for each range. If the outcome shows significant variation, the parameter must be determined with high accuracy. Conversely, if the outcome changes only slightly, an approximate value may be acceptable, or the parameter could potentially be excluded from the analysis altogether.

A parallel to sensitivity analysis is uncertainty analysis [6]. The uncertainty related to an LCA inventory, can be significant. Since it is the difference between alternatives which is of interest, and not the absolute values, it is crucial to take uncertainty into consideration when performing comparative LCA's.

4. Reporting and communication of results

Transparent reporting and clear communication of LCA results are essential for contextualizing the findings and enabling an informed evaluation of the results and conclusions. Every LCA report on textile for composites should include the following information:

Key product parameters and process issues:

Production technology

Lifetime of product

Location of production

Material conductivity and final product thermal resistance

Composite thickness

Relevant aspects of modelling

Time-frame of data;

Life cycle stages included;

The place/country/region of production modelled;

Type of electricity used and modelled: electricity mix (e.g., average grid medium voltage European grid (RER), site-specific power use (e.g., hydropower, coal));

Life cycle inventory: Foreground data and Background database and used background datasets

Goal and scope of the analysis

Purpose of the study;

Technical and modelling assumptions (e.g. prototype or commercial production, production description, production location, current performance or expected future development);

Type of LCA model applied (attributional, consequential, etc.);

The name of the entity commissioning the study;

LCA tool used (e.g., Simapro, GaBi, other), LCI database(s) used (e.g., ecoinvent, GaBi, ELCD, NREL, IDEA, other),

Impact category indicators used, always including the methods and the version numbers;

Sensitivity and uncertainty Analysis

To perform Sensitivity and Uncertainty analyses are highly recommended.

5. Learnings from the SustDesignTex microproject

The design of this report has been carried out at the same time as the TUL, Lodz University of Technology team was making progress in the realisation of the microproject 'Design and implementation of a fire-resistant composite made of natural fibres dedicated to the aviation industry, taking into account the principles of sustainable development' during the research stay in the University of Zaragoza. The SustDesignTex project team has collaborated on microprojects to ensure sustainability guidelines using LCA applied to different compositions of different composite alternatives using natural fibres.

The outcome of the long-term visit at the University of Zaragoza (UZ) 21.09-23.11.2024 developed by team follows all the recommendation from section 4. Reporting and communication of results.

6. Conclusions

Clear and precise reporting of Life Cycle Assessment (LCA) outcomes is vital for contextualizing the results and supporting an informed interpretation of the findings and conclusions.

This report presents a set of recommendations and guidelines essential for conducting a robust environmental assessment. The accurate definition of the functional unit and reference flow is fundamental to ensuring the reliability of comparisons across different materials and enabling the derivation of scientifically sound conclusions. Moreover, any LCA report related to textiles for composites should contain the information detailed in this report.

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