CIRC-UITS

Report on "S&C assessment & advisory services"

DELIVERABLE D3.2

Version 1

06/2025

Project Number: 101091490

Project Acronym: CIRC-UITS

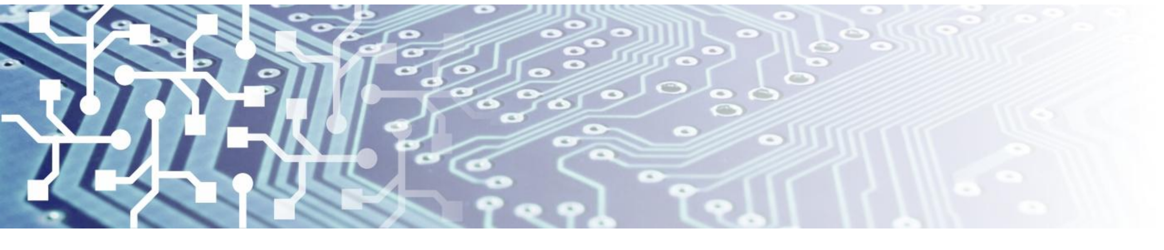
Project title: "Circular Integration of independent Reverse supply Chains for the smart reUse of IndusTrially relevant Semiconductors"

Starting date: 01/01/2023

Duration in months: 36

Call (part) identifier: HORIZON-CL4-2022-TWIN-TRANSITION-01

Topic: HORIZON-CL4-2022-TWIN-TRANSITION-01-07



Technical reference

Deliverable:	*D3.2*
Work Package:	WP3
Due Date:	30/06/2025
Submission Date:	30/06/2025
Start Date of Project:	01/01/2023
Duration of Project:	36 months
Organisation Responsible of Deliverable:	SUPSI
Version:	1.0
Status:	Final
Author name(s):	Giuseppe Landolfi, Christian Trisolini, Siro Dell'Ambrogio, Veronica Dosi, Simone Fasola, Alessandro Fontana
Reviewer(s):	OFFIS, MARAS
Type:	☐ Report X Other
Dissemination level:	☐ PU X SEN

Abstract

This deliverable presents the technical implementation and validation of the GRETA digital platform, enhanced during the CIRC-UITS project to support sustainability and circularity assessments in the semiconductor reverse supply chain. GRETA is a modular, web-based tool that enables both diagnostic and advisory functionalities across the entire product life cycle. It integrates LCA, LCC, SLCA, and CE assessment, and supports users in modeling, evaluating, and optimizing product alternatives through customizable scenarios. Key advancements during the project include the integration of EoL data from MARAS recycling simulations, LCA considering reuse and extended product lifetime scenarios, and the deployment of AI-powered advisory features such as a sustainability chatbot, hotspot identification, and best customization services. These functionalities were validated through three industrial pilots: Bosch (ECU), Continental (Tyre Sensor), and TNO (IME), which allowed practical testing and demonstration of the tool's performance and flexibility in real-world settings. The results from these pilots form the basis for final assessments and will be further elaborated and discussed in Deliverable D4.2.

List of acronyms

Abbreviation	Definition
API	Application Programming Interface
JSON	JavaScript Object Notation
REST	Representational state transfer
AI	Artificial Intelligence
DB	Database
RAG	Retrieval-Augmented Generation
LCA	Life Cycle Assessment
SLCA	Social Life Cycle Assessment
LCC	Life Cycle Costing
CE	Circular Economy
GHG	Greenhouse Gases
LCS&CA	Life Cycle Sustainability and Circularity Assessment
LCI	Life Cycle Indicator
IOT	Internet of Things
IIOT	Industrial Internet of Things
ERP	Enterprise Resource Planning
CAD	Computer-Aided Design
DPP	Digital Product Passport
BoM	Bill of Materials
UI	User Interface
DAG	Direct Acyclic Graph
EoL	End of Life
LLM	Large Language Model
EPD	Environmental Product Declaration
UMAP	Uniform Manifold Approximation and Projection
PCA	Principal Component Analysis
HTTP	Hypertext Transfer Protocol
URL	Uniform Resource Locator
CURL	Client URL
MCI	Material Circularity Indicator
PCB	Printed Circuit Board
ECU	Electronic Control Unit
ABS	Acrylonitrile Butadiene Styrene
EF	Environmental Footprint
PPS	Production Planning System

Table of contents

Introduction

Purpose of the Document

This document presents the technical developments and functional enhancements of the GRETA tool implemented during the CIRC-UITS project. It focuses on the system architecture, assessment and advisory features, and their validation process. The application of these functionalities within the specific pilot cases of the CIRC-UITS project is also addressed, while the discussion of results will be presented in the final deliverable, D4.2.

In addition to this technical report, Deliverable D3.2 includes a video demonstration showcasing the application of GRETA's functionalities to Pilot 2 (Continental), highlighting the tool's practical use in an industrial context.

Structure of the report

The report is structured into three main sections:

1. an overview of the pre-existing GRETA functionalities;
2. the technical description of new features developed within CIRC-UITS, including AI-based advisory services and extended assessment capabilities;
3. the validation of GRETA functionalities through three industrial pilots.

1. Overview of GRETA

This chapter has the main objective of providing the reader with the background needed to better understand the functioning of GRETA and its features showing the starting point on which the developments made in the context of the project are based.

This section will start with an overview of the architecture and of the innovative approach behind GRETA, then move on to the description of the main assessment functionalities and how these are managed between front-end and back-end, and then conclude with the presentation of the AI-based advisories, whose logics have been tested and validated in the project pilots whose results will be extensively described in the deliverable *D4.2 Pilot series production for the reference sectors*, expected at M36.

1.1 General Concept and Architecture

GRETA is a web, microservices-based, application designed to assess the sustainability and circularity performances of products and processes in manufacturing contexts. It offers diagnostic and advisory functionalities, enabling users to optimize their manufacturing practices and make data-driven decisions. GRETA has been tailored to meet the demands of manufacturing companies focused on sustainable early-stage product design. It empowers users to generate and compare different production manufacturing scenarios and their usage, leveraging the limited data typically available during the preliminary stages of product design. In response, the software delivers insightful sustainability profiles, harmonizing environmental, economic, social and circular aspects. This aids users in pinpointing the most eco-friendly and cost-effective options. It is a broad-spectrum tool whose basic functionalities have been developed and evolved in many European research projects such as CIRC-THREAD[1] and TREASURE[2].

The unique aspects of GRETA include the ability to introduce scenarios for each life cycle phase of a product, as well as for its assemblies (larger set of components), or individual components. This approach seeks to equip technical and operational decision-makers with the tools they need to fully understand the sustainability impacts of their design choices and act accordingly.

Its software architecture is structured into four main tiers:

1. *Front-End Layer*: Hosts the user interface, enabling access to GRETA's tools and services.
2. *Back-End Layer*: Composed of modular microservices, including the sustainability calculation engine, repository manager, and additional logic for sustainability-related features.
3. *Integration Layer*: Manages connections with external data sources and systems that GRETA either consumes or outputs to.
4. *Security Layer*: Handles authentication, authorization, and user management.

---

[1] **CIRC-THREAD**: EU project, H2020 programme, Grant Agreement No. 958448, https://circthread.com/

[2] **TREASURE**: EU project, H2020 programme, Grant Agreement No. 101003587, https://www.treasureproject.eu/

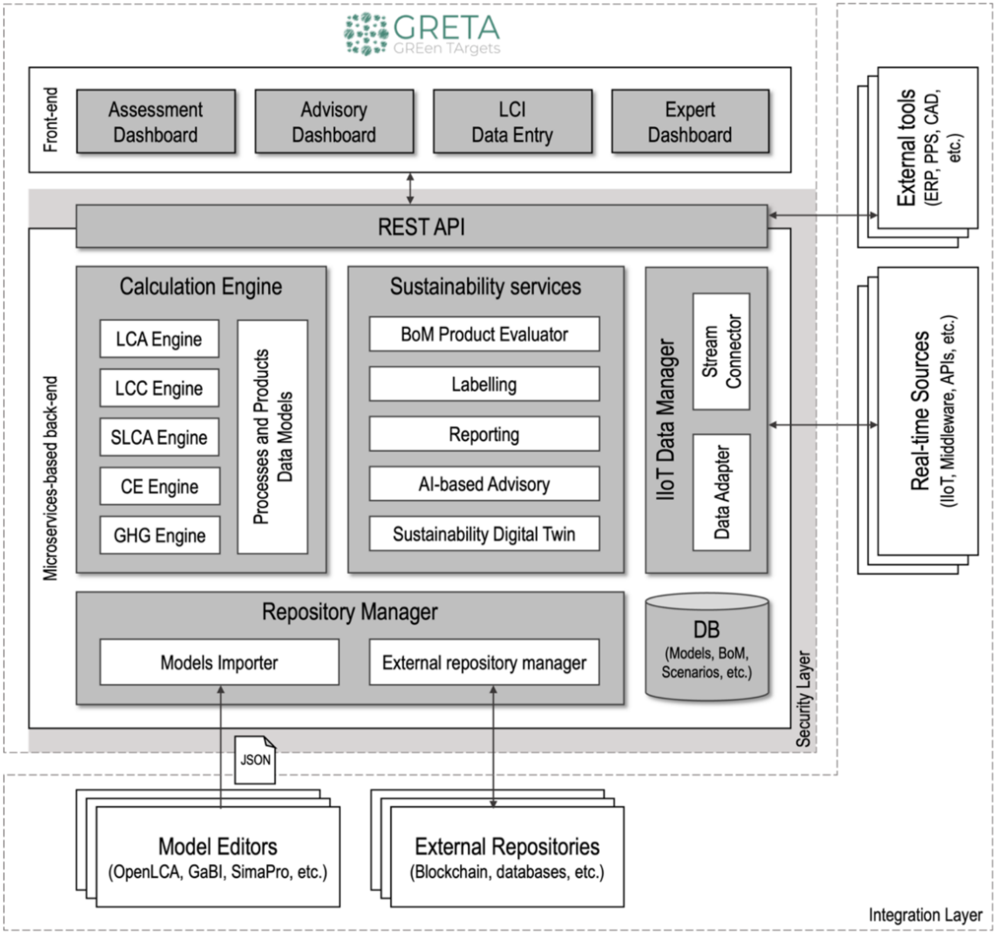


Figure 1 High-level architecture of GRETA

These layers run within a clustered environment, where each microservice is containerized. The cluster is managed by an orchestration system that supports scalability, fault tolerance, DevOps practices, and efficient resource use. The architecture has been designed to be flexible and is actively evolving, with the here described version which is reflecting the current deployment.

1.1.1 GRETA Front-End and Back-End Overview

The **front-end** of GRETA is a set of web interfaces that allow users such as experts, designers, and producers to interact with its features. It communicates securely with the back-end via REST APIs managed through a security layer. The front-end of GRETA includes several dashboards: the *Assessment Dashboard* which displays results, contribution trees, and comparisons; the *Scenario Customization Dashboard* which lets users create projects and input Life Cycle Inventory (LCI) data; the *Expert Dashboard*, intended for advanced users, that allows importing life cycle models and setting up scenario templates; and the *Advisory Dashboard* (some details will be presented in the following paragraphs) which assists users with intelligent suggestions and data-driven scenario generation.

From **back-end** side, GRETA operates through a suite of microservices, each responsible for different aspects of sustainability evaluation. In particular, the *Calculation Engine* is meant to execute different types of assessments like LCA, LCC, SLCA, Circular Economy (CE), and GHG, with scalable support for multiple methodologies. The *Sustainability Services* component provides added functionalities such as BoM-based evaluations, labelling, reporting, massive scenario creation, and *AI-based Advisory Service*s. This AI support includes capabilities like generating missing LCI data, optimizing scenarios for sustainability, analyzing parameter impact, forecasting, and chatbot guidance.

Such services layer also includes the *Sustainability Digital Twin Management* service, which integrates real-time and historical data, for example coming from the real production environment (from sensors, IoTs, etc.), into the life cycle models for more accurate and current assessments. This works alongside the *IIoT Data Manager*, responsible for collecting and integrating real-time data from smart devices.

All input and output data are centrally managed by the *Repository Manager*, which handles the storage of the sustainability models, manages user access control based on roles and domains, and supports the models import from external LCA tools. It also facilitates integration with external repositories, including Digital Product Passports (DPPs), ensuring data security, traceability, and compliance.

The GRETA integration layer ensures connectivity with external systems for both input and output. It supports model editors, real-time data sources, external databases, and enterprise systems like ERP and CAD. For example, CAD integration enables real-time impact assessment during the design phase, helping optimize material choices and energy use while promoting circular economy principles. Within the integration layer, certain services have been made available by means of a suite of REST APIs, safeguarded by a security layer controlling access. More details about the exposed APIs will be widely described within the section 2.2.2.

1.2 GRETA Approach and the pre-existing Functionalities

The workflow in GRETA begins with experts who model the product life cycle by means of existing sustainability tools like OpenLCA[3], GaBi[4], or SimaPro[5]. These models, exported in a standard format, are then imported into GRETA for analysis and transformation. Thanks to GRETA, the experts can define the C*ustomization Spaces*, which is the set of all processes characterizing the life cycle of the system being analyzed, accompanied by the rules that define the existence domain boundaries of the model parameters the user is willing to vary (customize) during the LCS&CA, creating more specific processes or investigate alternatives, intended as different product lifecycle scenarios. The Customization Spaces establish which are the parameters of the model that can be customized, the possible values they can assume and the possible constraints or dependencies amongst each other. The aim of the customization spaces is thus to define the rules through which the user can customize each process and therefore customize the system life cycle. Examples of these rules are: (i) range validation (minimum and maximum values) related to the amount of an input flow (e.g. min and max of the quantity of raw material inputs of a process); (ii) option values assignable to the amount of an input flow (e.g. different physical dimensions of a product); (iii) possible predetermined value or options; (iv) alternative process providers assignable to an input flow (e.g. the list of raw materials, energy mixes used during the production phase, transportation alternatives for the system); (v) possible formulas for combining numerical values (useful when the aim is to calculate an amount of an input flow which is obtained as linear combination of a set of parameters, such as the volume of a specific product obtained by its dimensions); (vi) possible dependencies between variables (e.g. constrain that drives the insertion of a parameter only if another parameter has previously been inserted, such as the dimensions asked to the end-use depending on the shape of the product) and (vii) possible external real-time data sources (like sensors, IoT, etc.) from which the data of a given parameter can be acquired.

In addition to the Customization Spaces, the novel modelling approach underlying GRETA introduces the *Scenario Template* concept which is the entity that enables the combination of multiple customization spaces and the related models generated by an existing sustainability editor like OpenLCA. Moreover, it manages

---

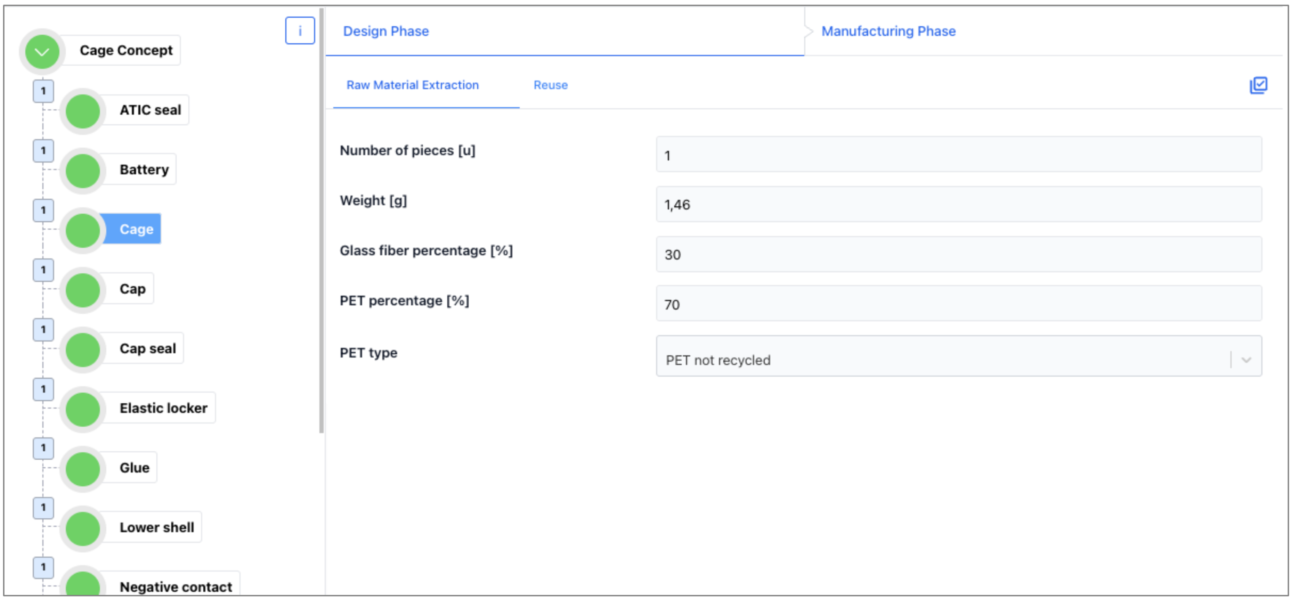
[3] **OpenLCA**: https://www.openlca.org/
[4] **GaBi**: https://sphera.com/
[5] **SimaPro**: https://simapro.com/

the association with the life cycle phases, such as raw material extraction, manufacturing, use, and end-of-life, providing a unified, parametrized life cycle model of the system in analysis.

1.2.1 Assessment Modules

Following the configuration (alias Customization Spaces) formalized by the sustainability experts, the end-users (i.e. manufacturers or product designers) can use GRETA to create and customize scenarios (intended as product alternatives) based on pre-defined scenario templates. They can adjust process parameters either manually, via IoT data, or from expert pre-defined options.

The scenario customization is streamlined and manufacturer-friendly, organized by life cycle phases and processes. If needed, the customization may follow the Bill of Materials (BoM) structure, with each component customized individually. Once all inputs are provided, the sustainability assessment can be executed.



Number of pieces [u]: 1

Weight [g]: 1,46

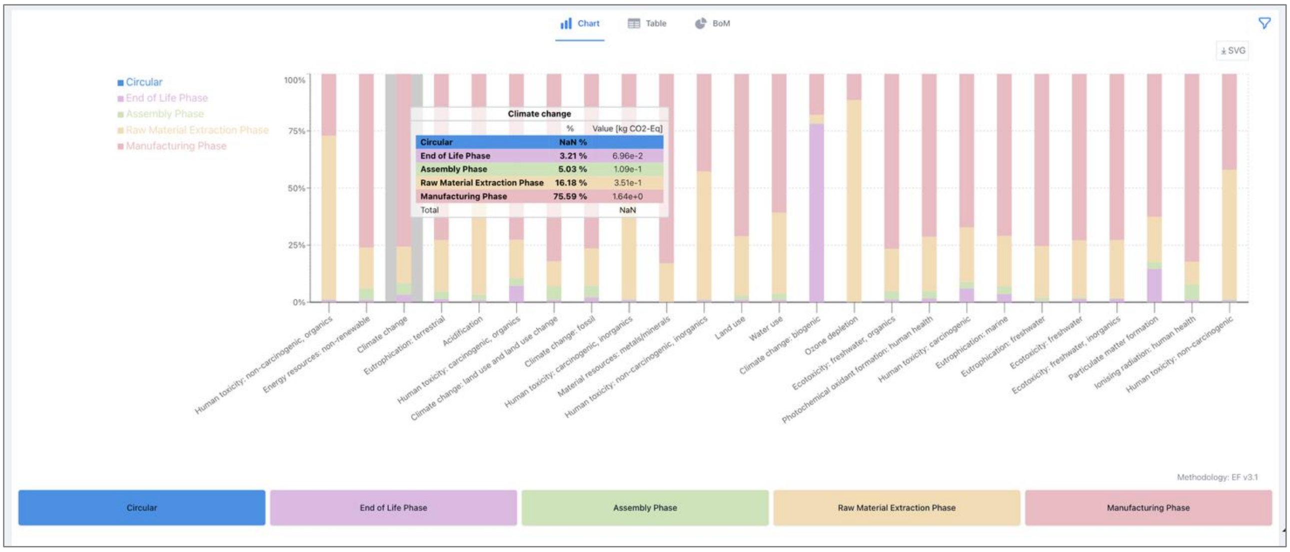
Glass fiber percentage [%]: 30

PET percentage [%]: 70

PET type: PET not recycled

Figure 2 Example of a BoM-based scenario customization (Continental use-case)

GRETA provides two different ways to show the assessment results: (1) a bar chart which allows the manufacturer to see how each life cycle phase affects the sustainability indicators, which is a view useful for significant issues identification; (2) a tabular view where numerical values of each indicator per each phase are shown. In the example depicted in Figure 3**Errore. L'origine riferimento non è stata trovata.** the bar chart shows the LCA assessment results calculated by means of EF v3.1 methodology (Environmental Footprint 3.1 version): in this case the indicator related to the climate change is mainly affected by the manufacturing phase (about 75%).

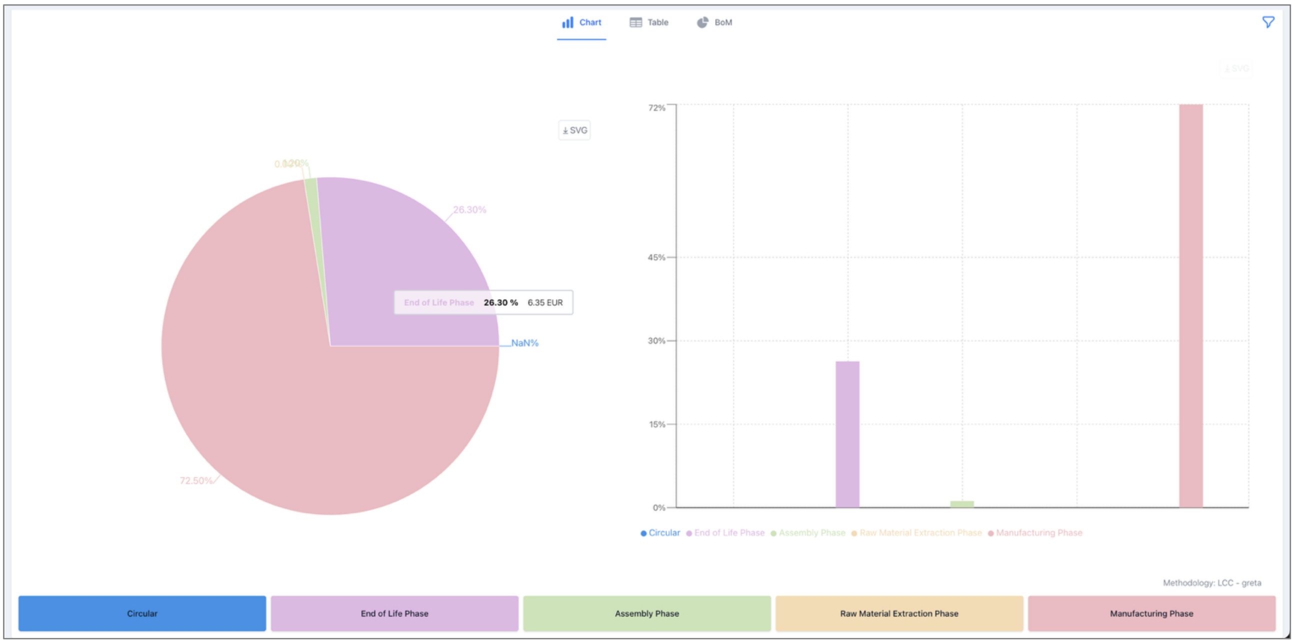


Climate change

	%	Value [kg CO2-Eq]
Circular	**NaN %**	
End of Life Phase	**3.21 %**	6.96e-2
Assembly Phase	**5.03 %**	1.09e-1
Raw Material Extraction Phase	**16.18 %**	3.51e-1
Manufacturing Phase	**75.59 %**	1.64e+0
Total		NaN

Figure 3 LCA assessment result along the Life Cycle (Continental use-case)

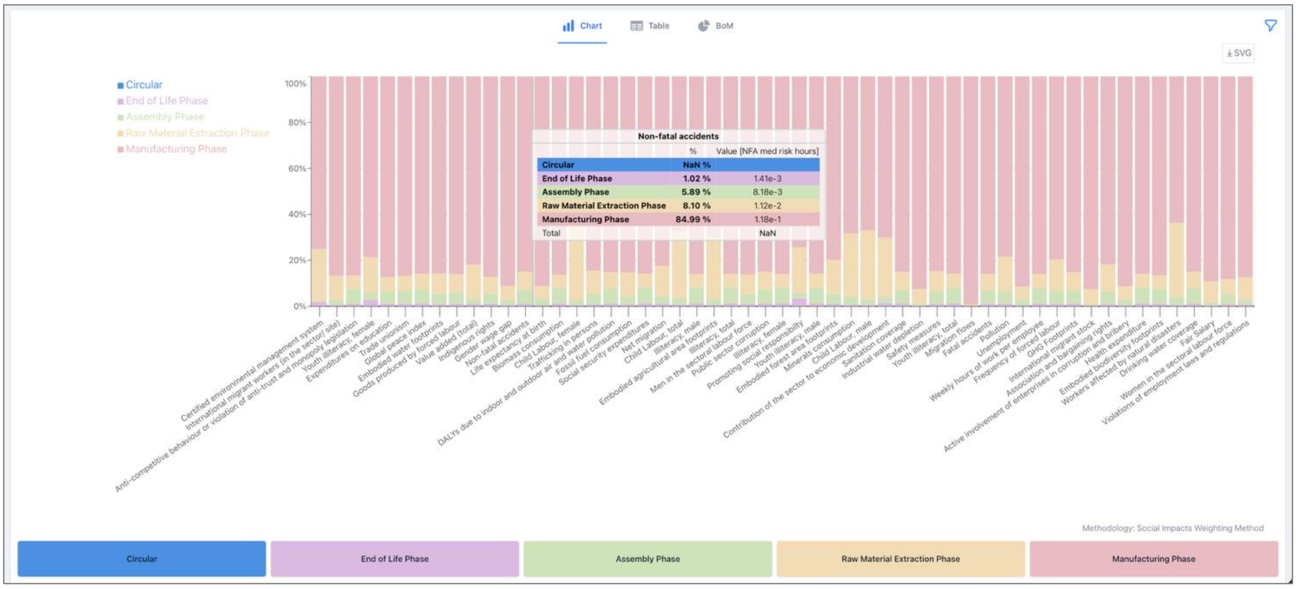
If needed, the user can also focus on more economical aspects of the product subject of the assessment simply by switching to the panel dedicated to show the LCC assessment results, as presented in Figure 4.



End of Life Phase **26.30 %** 6.35 EUR

Figure 4 LCC assessment result along the Life Cycle Phases (Continental use-case)

In the example depicted in Figure 5 the chart shows the SLCA assessment result along the life cycle phase: for each social indicator, value and unit of measure are shown.



Non-fatal accidents

	%	Value [NFA med risk hours]
Circular	**NaN %**	
End of Life Phase	**1.02 %**	1.41e-3
Assembly Phase	**5.89 %**	8.18e-3
Raw Material Extraction Phase	**8.10 %**	1.12e-2
Manufacturing Phase	**84.99 %**	1.18e-1
Total		NaN

Figure 5 SLCA assessment along the Life Cycle Phases (Continental use-case)

1.2.2 Advisory Services

As introduced before, GRETA is a digital platform developed to help companies to perform sustainability assessments and calculations, enabling more informed decision-making regarding the customization of their products and processes for improving the sustainability aspects. GRETA, by integrating advanced algorithmic solutions, allows businesses to automate complex analyses, reducing reliance on manual, repetitive tasks and accelerating the identification of sustainability opportunities.

GRETA offers two advanced advisory services, named *Best Customization* and *Hotspot Identification*, both of which are built upon algorithm-driven methodologies to support users in enhancing the sustainability performance of their operations.

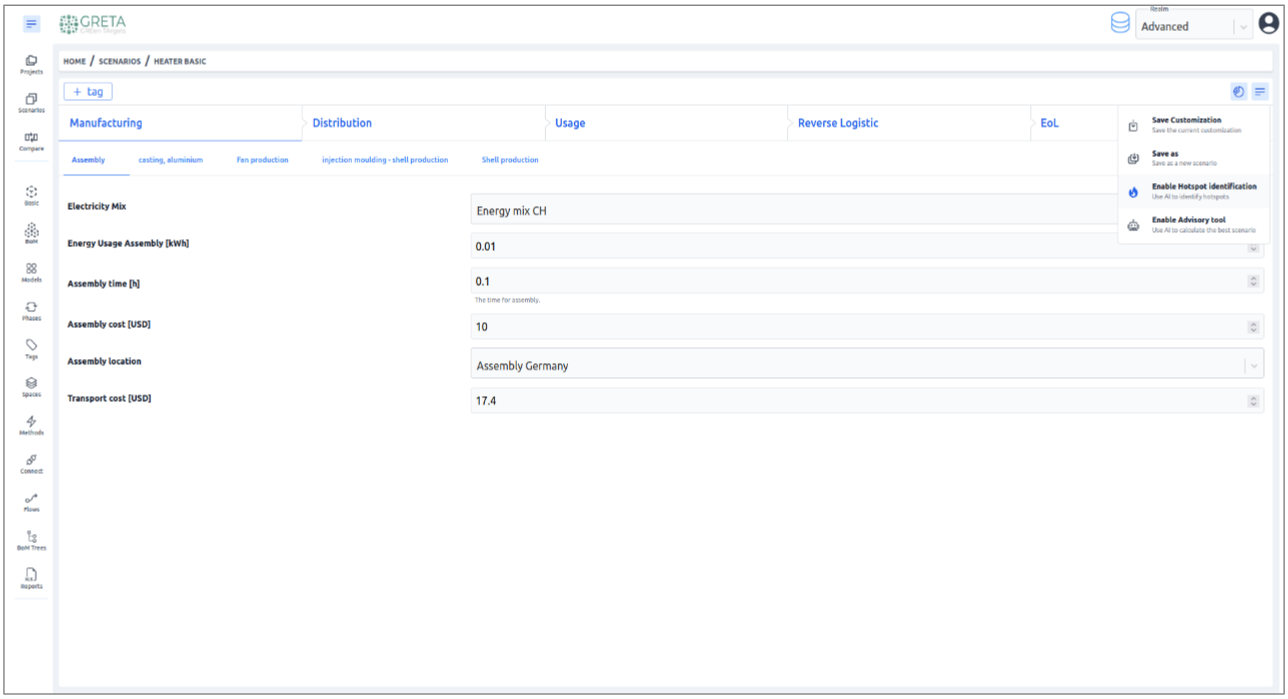
- **Hotspot Identification** deploys a ranking algorithm to detect which items, phases, or parameters within a product life cycle have the highest environmental impact. Companies can prioritize their sustainability efforts by identifying these critical "hotspots" addressing resources toward changes that will yield the most substantial improvements. This targeted approach enhances the efficiency and effectiveness of sustainability initiatives.
- **Best Customization** focuses on optimizing production process parameters with the aim to reach a balance between minimizing environmental impact and reducing production costs. It uses a parameter optimization algorithm that considers production constraints defined by sustainability experts within GRETA. These constraints are configured during the creation of scenario templates, allowing users to tailor the optimization process to specific industrial needs and limitations. This service is particularly useful during the early stages of product development or redesign, where users can identify the optimal combination of parameters that align with sustainability goals.

The final goal of these two advisory services is to guide users through the decision-making process by offering actionable insights based on the sustainability footprint of their products and processes. These GRETA features can be applied at different stages of the product life cycle: during the eco-design phase, the Best Customization service can suggest parameter sets that minimize both cost and environmental impact; post-analysis instead, the Hotspot Identification service helps to interpret sustainability results and to determine which parts of the product or process deserve more attention.

These advisory services have been developed within the DaCapo[6] project (more details can be found in the deliverable *D3.3 DaCapo digital platform, middleware and knowledge and data analytics tools*). In the context of the CIRC-UITS project, these services will be used to support the decision-making process in optimizing the pilot-related products from a sustainability perspective. It will therefore be an opportunity for SUPSI to test and validate these services in a new context.

1.2.2.1 User Interfaces

The front-end layer allows users to access these advisories through the GRETA UI. The Hotspot Identification has been implemented as a pop-up window that can be activated during the scenario customization to highlight the most environmentally impactful products, phases, and processes. When the Best Customization is triggered first, the hotspot pop-up appears by default, ensuring users are aware of key optimization targets before proceeding. The Best Customization advisory, in contrast, is presented as a side panel on the right of the interface, displaying configuration options and real-time indicators to track the optimization process.



Electricity Mix: Energy mix CH

Energy Usage Assembly [kWh]: 0.01

Assembly time [h]: 0.1

The time for assembly.

Assembly cost [USD]: 10

Assembly location: Assembly Germany

Transport cost [USD]: 17.4

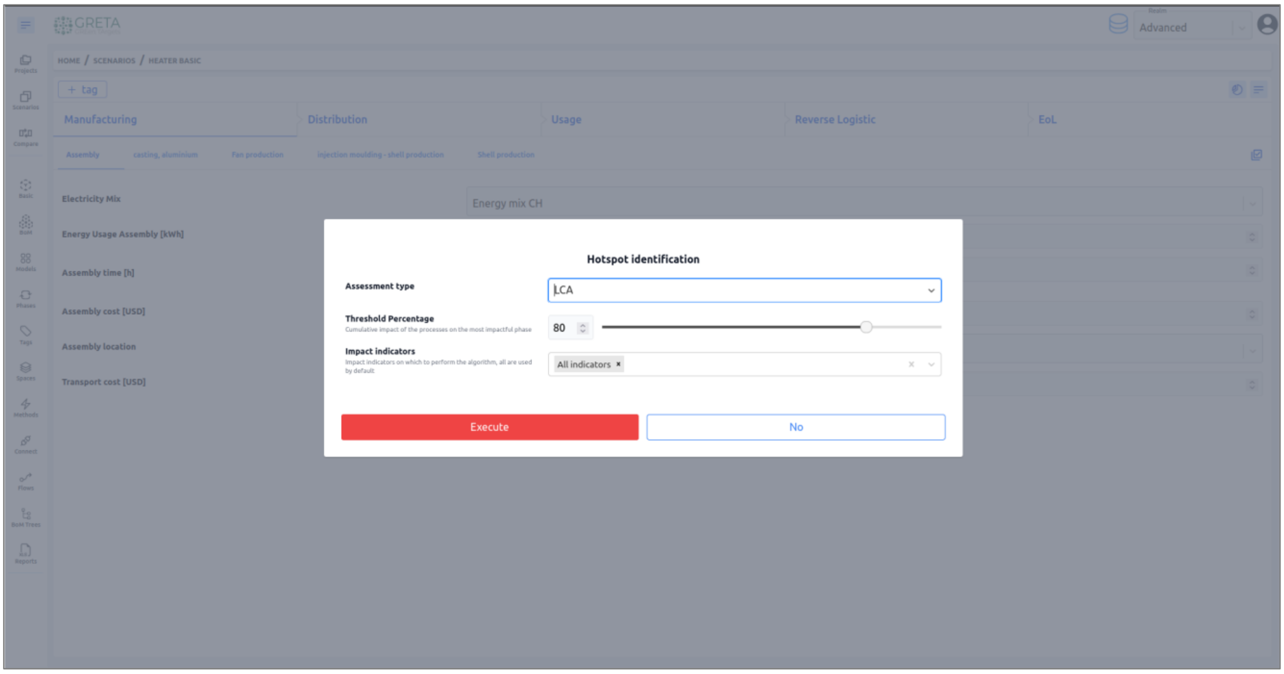
Figure 6 Advisory Services menu

Hotspot Identification Advisory Service

The Hotspot Identification Advisory Service allows the users to configure a set of different parameters according to their needs: the assessment type parameter (currently limited to Life Cycle Assessment but in the next versions it is planned to extend it also to LCC and SLCA), the threshold percentages parameter for the cumulative impacts, and the parameter related to the list of the selected environmental indicators.

---

[6] **DaCapo**: EU project, H2020 programme, Grant Agreement No. 101091780, https://www.dacapo-project.eu/



Hotspot identification

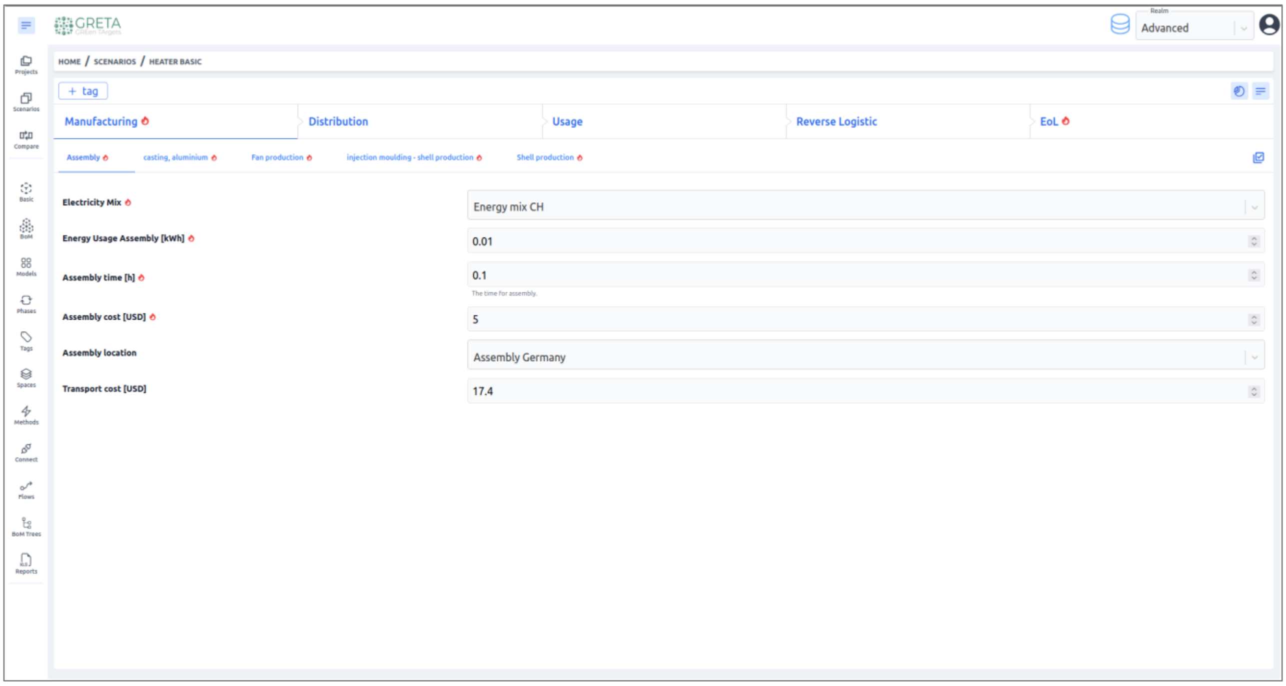
Assessment type: LCA

Threshold Percentage: 80
Cumulative impact of the processes on the most impactful phase

Impact indicators: All indicators
Impact indicators on which to perform the algorithm, all are used by default

Figure 7 Hotspot Identification pop-up

Once the advisory service is executed, the most impactful elements, in terms of processes and parameters, are visually marked in the interface (with a flame as shown in Figure 8).



Electricity Mix 🔥: Energy mix CH

Energy Usage Assembly [kWh] 🔥: 0.01

Assembly time [h] 🔥: 0.1
The time for assembly.

Assembly cost [USD] 🔥: 5

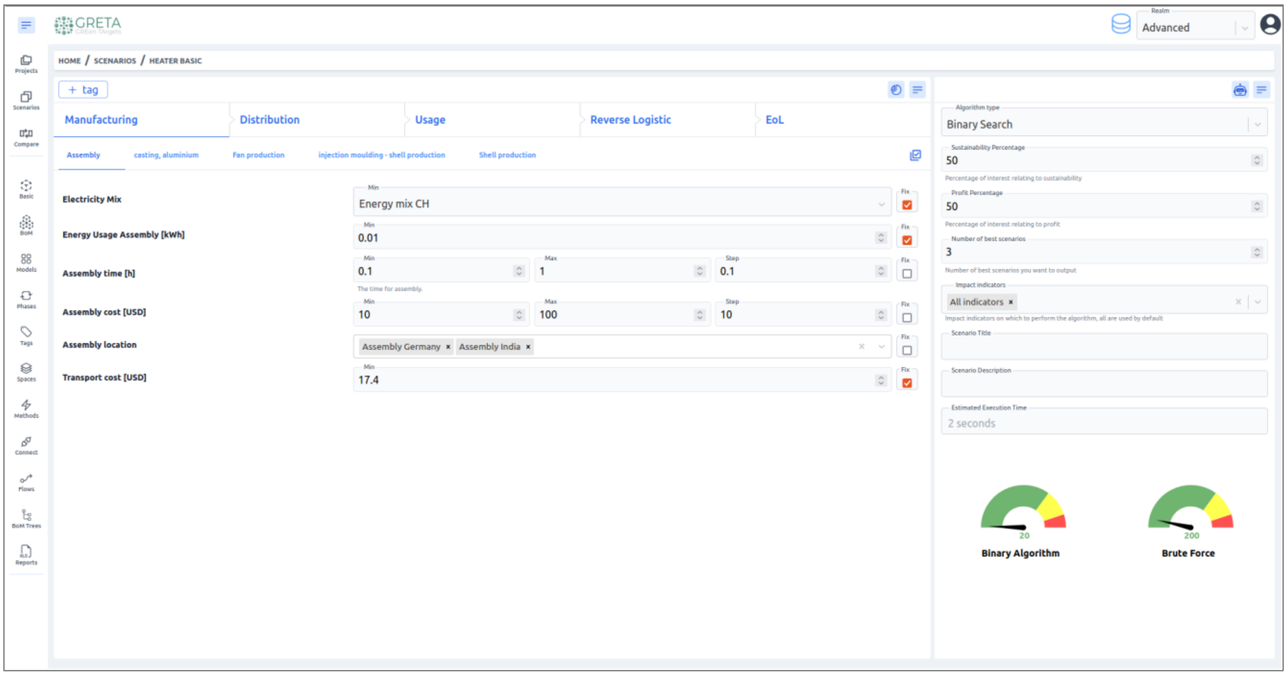
Assembly location: Assembly Germany

Transport cost [USD]: 17.4

Figure 8 Hotspot identification results

Best Customization Advisory Service

The Best Customization Advisory Service offers a contextual menu where users can define the optimization approach, assign weights to sustainability and profit metrics, set the number of scenarios to generate, and estimate the processing time. This advisory service provides gauge charts meant to indicate if the number of parameter combinations exceeds the safe computational threshold. Users can then fine-tune each parameter by fixing values or setting numeric ranges or option lists. This advisory service can automatically exclude invalid customizations based on constraints derived from the scenario template, which are encoded as a directed acyclic graph.



Realm: Advanced

Electricity Mix — Min: Energy mix CH — Fix ☑

Energy Usage Assembly [kWh] — Min: 0.01 — Fix ☑

Assembly time [h] — Min: 0.1 — Max: 1 — Step: 0.1 — Fix ☐
The time for assembly.

Assembly cost [USD] — Min: 10 — Max: 100 — Step: 10 — Fix ☐

Assembly location — Assembly Germany × Assembly India × — Fix ☐

Transport cost [USD] — Min: 17.4 — Fix ☑

Algorithm type: Binary Search

Sustainability Percentage: 50
Percentage of interest relating to sustainability

Profit Percentage: 50
Percentage of interest relating to profit

Number of best scenarios: 3
Number of best scenarios you want to output

Impact indicators: All indicators ×
Impact indicators on which to perform the algorithm, all are used by default

Scenario Title:

Scenario Description:

Estimated Execution Time: 2 seconds

Figure 9 Best customization parameter space definition

1.2.2.2 Back-end

This paragraph summarizes the algorithmic solutions adopted for both consulting services.

Hotspot Identification Advisory Service

The Hotspot Identification Advisory Service exploits GRETA calculation engine to evaluate environmental impacts across the items of the product and its related processes.

Given a BoM of a product and the calculation engine exposed by GRETA, the Hotspot Identification Advisory Service can obtain the sustainability impacts for each phase associated to each item of the BoM. The service computes both direct (self-impact) and aggregate (total impact) values. The service identifies and returns the most critical parameters for the environmental performances by ranking the self-impacts relative to the entire product impact and then analysing the cumulative effects along the life cycle phases.

Best Customization Advisory Service

The Best Customization Advisory Service begins by building an *optimization space* which is a set of all possible valid parameter combinations. This space is filtered using a Direct Acyclic Graph (DAG)-based constraint logic to avoid scenarios unfeasible according to manufacturing point of view. GRETA provides two optimization algorithms: a brute-force method, which guarantees finding the optimal solution but is resource-intensive, and a binary search method, which is faster but may return a local optimal solution. Both methods rely on the assessment calculations engine provided by GRETA. More in details, the solution calculates a GRETA score, which combines profit and sustainability metrics according to user-defined weights. These scores are then normalized on a scale from 0 to 10 and used to rank the generated scenarios. The best-performing configurations are stored and remain accessible for further analysis and refinement.

Both services expose a dedicated set of APIs: the Hotspot Advisory API allows users to identify key impact areas, while the Best Customization Advisory API provides optimized parameter sets that respect production constraints. These APIs are fully integrated with GRETA core functionality.

1.3 Validation and Testing in CIRC-UITS

The legacy functionalities, although developed before the project, were tested and validated within the CIRC-UITS pilots and use cases as required by the project methodology outlined in D3.1.

2. Features Developed in CIRC-UITS

This chapter is dedicated to describe the developments carried out during the project, starting from the integration of the SOCA Database in the product modeling (and consequent import of the models into GRETA), passing through the creation of a new LCA assessment approach that includes the product reuse and the EoL data during the recycling simulations, till to the development of a series of advanced functionalities (some of which AI-based) both to support the expert in the modelling phase and to enable GRETA to be integrated with the rest of the platform allowing third-party applications to exploit its mechanisms.

2.1 Extended Assessment Capabilities

2.1.1 Integration of the SOCA Database for Unified BoM-Based Modelling

Thanks to the flexibility of GRETA architecture and its exposed services, GRETA is able to host sustainability models whose processes can be derived from any type of sustainability database the experts desire to consider, such as Ecoinvent[7], SOCA[8], PSILCA[9], etc.

In the specific context of the CIRC-UITS project, the SOCA database was adopted and integrated into GRETA for the first time. As described in Deliverable D3.1, SOCA is a novel database designed to support not only environmental assessments but also social (SLCA) and economic (LCC) evaluations using the same life cycle inventory (LCI) structure employed for traditional LCA. This means that a single BoM-based model can be used to generate results across all three dimensions. This characteristic made SOCA particularly suitable for CIRC-UITS, where some pilot cases required a broader sustainability perspective while maintaining high modelling efficiency and coherence. Its integration enabled GRETA to offer a harmonized assessment workflow where users could seamlessly explore trade-offs and synergies between LCA, SLCA, and LCC within the same product model.

2.1.2 LCA Including Product Reuse Scenarios

Unlike traditional LCA tools that require duplicating and restructuring models to represent reuse scenarios, GRETA enables the modelling of reuse directly within the scenario configuration interface, without altering the core structure of the product model. This represents a major advantage in terms of modelling efficiency, flexibility, and usability, especially during iterative design and assessment phases.

Within the CIRC-UITS project, the potential to configure product reuse scenarios in GRETA was successfully demonstrated, taking advantage of its flexible scenario customization environment. Three distinct modelling approaches were enabled to represent different reuse strategies directly within the LCA configuration:

1. Full Product Replacement: Users can define how many times the entire product is replaced over a specified reference period. For example, if the analysis covers 20 years and the product has a 10-years lifespan, one replacement cycle of the whole product is configured.
2. Component-Level Replacement: It is possible to specify, for each component, how many replacements are needed to ensure that the overall product meets its expected lifespan. For instance, if the product is intended to last 10 years but a component lasts only 5 years, that component will be replaced once in the model.

---

[7] **Ecoinvent**: ecoinvent is a global, non-profit organization that develops and maintains a comprehensive life cycle inventory (LCI) database, https://ecoinvent.org/ .

[8] **SOCA**: SOCA database is an add-on for the ecoinvent database, providing social impact data to facilitate Life Cycle Sustainability Assessments (LCSA), https://nexus.openlca.org/database/soca .

[9] **PSILCA**: PSILCA, which stands for Product Social Impact Life Cycle Assessment, is a database developed by GreenDelta for Social Life Cycle Assessment (S-LCA), https://nexus.openlca.org/database/PSILCA .

3. Variable Product Lifespan: The product lifespan can be treated as a configurable parameter. This is useful in early design phases, when the expected lifetime is not yet defined, or when comparing alternative design scenarios and reuse strategies (such as full or partial replacement), enabling a better understanding of the environmental impact over different usage durations.

These configurations were implemented seamlessly thanks to GRETA architecture, which allows users to define reuse logic and parameter behaviors within the scenario templates. This significantly reduces the modelling burden, improves reproducibility, and enhances the tool’s ability to support circular design strategies in LCA studies.

2.1.3 Integration of End-of-Life (EoL) Data via MARAS Recycling Simulations

In the context of the CIRC UITS project, the End-of-Life phase, with a focus on recycling, was analysed by the partner MARAS through dedicated recycling simulations. To ensure that this phase was properly accounted for in the overall life cycle assessment, GRETA was configured to incorporate the outputs of these simulations.

MARAS provided SUPSI with the results of the recycling simulations, which included key parameters such as recovery rates, material losses, energy consumption, and emissions. Based on these values, SUPSI customized the End-of-Life processes within GRETA, replacing default datasets with project specific data. This allowed the recycling phase to be represented in a way that reflected the actual performance simulated within CIRC UITS, improving the accuracy and relevance of the sustainability assessment.

This integration supported coherence between the different activities within the project, consolidated collaboration between partners, and demonstrated once again the flexibility of GRETA in adapting to external inputs. It also reinforced the alignment with the circularity objectives of the project by ensuring that recycling performance was considered as an integral part of the life cycle modelling.

2.2 Advanced Advisory Features

2.2.1 AI-based Chatbot for LCA Expert modelling assistance

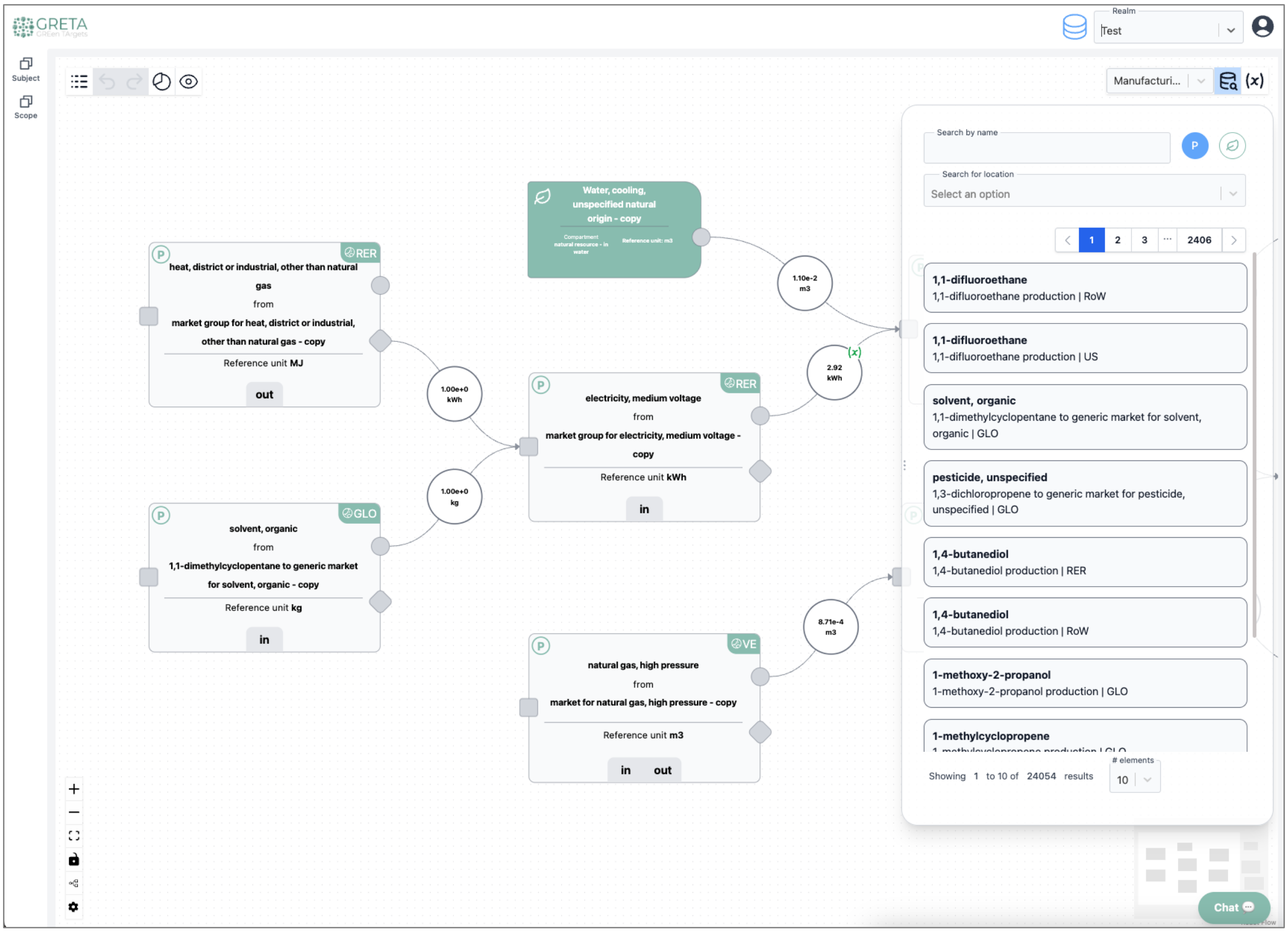
Life Cycle Assessment (LCA) modelling is a highly complex process in sustainability analysis. It requires domain expertise, data interpretation, and manual effort to accurately model products and processes environmental impacts. The challenge is further amplified by the huge volume of data made available from inventory databases. Moreover, the existing sustainability modeling tools like OpenLCA are powerful and widely used for Life Cycle Assessment (LCA) but they also present several limitations that can affect their usability, scalability, and decision-making support:

- *Complexity and usability*: existing tools require significant expertise in LCA methodology which can be a barrier for non-experts or small businesses. Users often need to manually input data or build models from scratch, which is time-consuming and prone to error.
- *Lack of decision-support functionalities*: existing tools don’t provide any advisory services or decision guidance, such as identifying hotspots or suggesting more sustainable alternatives.
- *No integration capabilities*: limited integration with production environment, IoT devices, or legacy systems useful for real-time or automated data exchange.
- *“Static” modeling approach*: to perform a comparative analysis of multiple product alternatives, existing sustainability modeling tools require duplicating models and making manual adjustments.

Given these limitations, there is a critical need for intelligent AI-driven advisory systems to enhance knowledge retrieval, similarity analysis, and automated advisory that can significantly improve the efficiency and accuracy of LCA modeling. To tackle these challenges, a **multi-agent AI-based advisory system** has been developed, integrating **Retrieval-Augmented Generation (RAG)** and **graph-based knowledge** representation to support LCA experts in sustainability modelling. This system, based on a **multi-agent supervisor framework**, dynamically orchestrates AI agents and tools based on user queries. Furthermore, this system lays the foundation for future advanced solutions like:

- *ML/AI solutions* are meant to analyze existing process structure databases in order to help users model processes correctly. For instance, the simple task of modeling the transportation process of a material requires a precise model structure that can be inferred by existing databases. This could both work as a validation tool for existing models as well as a guided mechanism to create valid processes, reducing the workload and speeding up model creation.
- *Natural language-driven modelling* enables users to describe processes in everyday language, allowing AI to construct or modify LCA models accordingly (e.g. "*Add a waste-water treatment stage after the textile dyeing process*").
- *Autonomous Process Generation* by means of large language models and domain-specific knowledge graphs is meant to generate new and accurate LCA processes from scratch.
- *Context-Aware inputs/outputs suggestion* can automatically propose upstream or downstream processes based on semantic understanding of the involved product and processes, accelerating model completion and improving accuracy.

Figure 10 shows a preliminary version of the GRETA model editor that allows experts to model products and processes from a sustainability perspective. This editor (developed in others research projects) tries to overcome the limitations of existing editors integrating the agentic AI-based advisory system, subject of this paragraph. Since the GRETA model editor is currently under development, the sustainability models of the project pilots have been formalized by means of OpenLCA exploiting the functionality provided by GRETA to import models coming from third-party applications. However, in order to demonstrate the goodness of the solution here presented, the experts made a combined use of OpenLCA, from which they formalized the final models, with the AI-based advisory system here described.



1,1-difluoroethane
1,1-difluoroethane production | RoW

1,1-difluoroethane
1,1-difluoroethane production | US

solvent, organic
1,1-dimethylcyclopentane to generic market for solvent, organic | GLO

pesticide, unspecified
1,3-dichloropropene to generic market for pesticide, unspecified | GLO

1,4-butanediol
1,4-butanediol production | RER

1,4-butanediol
1,4-butanediol production | RoW

1-methoxy-2-propanol
1-methoxy-2-propanol production | GLO

1-methylcyclopropene

Showing 1 to 10 of 24054 results

Figure 10 GRETA Model Editor

One of the key agents that leverages the AI-based advisory system is the **sustainability chatbot**, fine-tuned on sustainability-related datasets. This chatbot is the primary interface for user interactions, it responds to natural language queries leveraging on a Retrieval-Augmented Generation (RAG) mechanism that dynamically gather relevant knowledge from a graph-based database. Unlike pre-trained AI assistants, this chatbot integrates real-time sustainability insights, producing responses that remain contextually accurate.

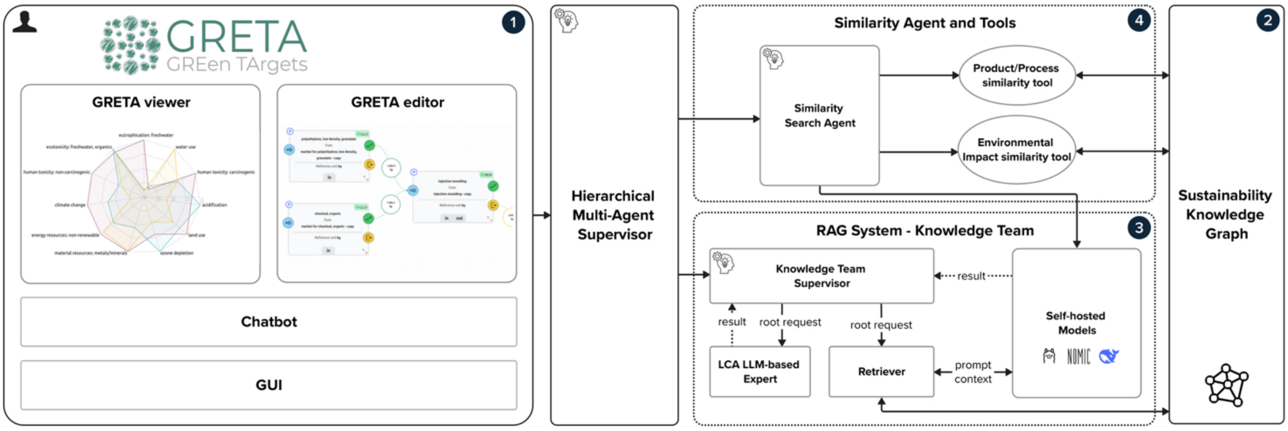


Figure 11 High level architecture of the RAG System

The second component is a **similarity search tool**, designed to assist users in searching relevant products and processes based on user's natural language-based input. This tool, exploiting a semantic similarity analysis, compares text provide by users against precomputed **embeddings** meant to find the best matches. These embeddings represent LCA-related entities (such as materials, manufacturing processes and energy consumption) and are obtained by exploiting both nodes properties and their graph topology allowing the system to retrieve and suggest the most relevant existing entities.

In this regard, an AI-enhanced ecosystem to support Life Cycle Assessment (LCA) experts throughout the modeling and decision-making process has been designed. This ecosystem is built around two key tools: GRETA Viewer and GRETA Model Editor.

- *GRETA Viewer* enables real-time visualization and analysis of LCA results. By adjusting model parameters, users can observe how interconnections and environmental impacts change dynamically, facilitating eco-design and product customization.
- *GRETA Model Editor* is a web-based application for building complex LCA models using either standard databases, like ecoinvent, or custom user inputs. Its intuitive flow-based interface allows creation of process networks with both fixed and parameterized data.

These tools provide the interfaces for our advanced AI services: (i) An **AI Chatbot**, served by our Life Cycle Assessment (LCA) advisory system with Retrieval-Augmented Generation (RAG) capabilities provides contextual support to users inside both GRETA tools, answering technical and data-related questions. (ii) A **Process Similarity Engine** that uses embeddings and a graph database to retrieve the most relevant LCA processes based on user input. Together, these systems aim to empower LCA experts by offering intelligent assistance during model development, enabling faster, more consistent, and informed environmental decision-making.

2.2.1.1 Sustainability Knowledge Graph

The developed system is based on a **graph database** to semantically represent product and processes for Life Cycle Assessment (LCA). Existing sustainability databases, that contains structured data across several industrial sectors (energy, manufacturing, transportation) describing inputs (raw materials, energy) and outputs (products, emissions, wastes), can be imported in this graph database and be part of the knowledge.

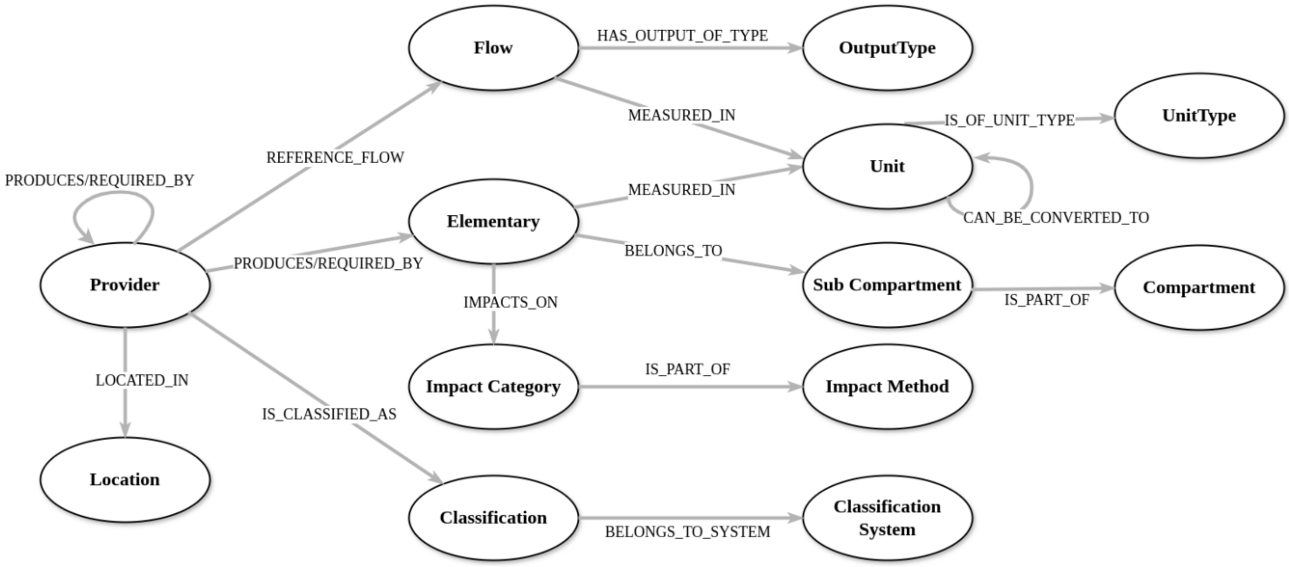


Figure 12 Graph database structure representing the sustainability data

Figure 12 shows a simplified version of the graph database structure and its key features are**:**

- *Nodes* representing *processes* with descriptive properties
- Semantic *relationships* showing *dependencies* and *outputs*
- *Integration capabilities* for external data (IoT, sustainability databases)
- *Geospatial* information linking processes to *locations*

The **embedding architecture** combines transformer-based text embeddings (by means of nomic-embed-text model) for textual properties and the GraphSAGE[10] algorithm to incorporate neighborhood information and graph topology. These are stored in the graph nodes, enabling fast similarity queries and integration with large language models for retrieval-augmented generation. This hybrid approach combines traditional graph-based reasoning with neural network representations, supporting both structured queries and semantic understanding for comprehensive environmental impact assessment.

2.2.1.2 RAG System – Knowledge Team

The **RAG System** is an advanced Life Cycle Assessment (LCA) advisory system, powered by two specialized AI agents that work collaboratively:

- The **LCA Expert (Fine-Tuned LLM)** that is a domain-specialized Large Language Model (LLM) fine-tuned on LCA methodologies and standards. It provides expert-level reasoning and ensures methodological consistency based on structured environmental inventory data from sustainability databases like ecoinvent, Environmental Product Declarations (EPDs) and peer-reviewed LCA literature and databases. This agent can be exploited also by non-expert users to better understand sustainability and LCA-related concepts. The LCA Expert Agent interprets queries, applies domain knowledge, and ensures alignment with best practices in sustainability and impact assessment.
- The **Knowledge Retrieval Agent (RAG + Graph Database)** This Retrieval-Augmented Generation (RAG)[11] system interfaces with a Graph Database structured from a set of sustainability databases like ecoinvent. It dynamically retrieves up to date relevant data, including processes, material flows, and impact factors, using a confidence-scoring framework that evaluates source credibility, data completeness, and temporal relevance. It automatically collects the up-to-date relevant data including processes, material flows, and impact factors by evaluating a confidence-based that rates source reliability, data completeness, and recency.

Together, these agents enable a robust, transparent, and adaptive advisory system. The LCA Expert Agent provides deep analytical reasoning, while the Knowledge Retrieval Agent ensures factual accuracy and structured knowledge access. Their collaboration ensures contextually accurate, methodologically sound, and data-driven insights for LCA experts.

2.2.1.3 Similarity Agent and Tools

The similarity search process begins with a user query formulated in natural language via a prompt. This query is processed by a multi-agent system, which includes an agent supervisor trained to route the request based on the specific use case. Multiple tools, connected to the supervisor agent, have been designed to retrieve the most relevant processes related to the user's request base on different criteria: (i) **Process/Product description similarity**: based on the process/product structure and type; (ii) **Environmental**

---

[10] **GraphSAGE**: William L. Hamilton, Rex Ying, and Jure Leskovec. Inductive representation learning on large graphs, 2018.

[11] **RAG System**: Shi-Qi Yan, Jia-Chen Gu, Yun Zhu, and Zhen-Hua Ling. Corrective retrieval augmented generation, 2024.

impacts similarity: based on process impacts. This tool can be used to search processes with similar impact values, it is used in combination to the previous one in order to avoid finding processes that are very different but with similar impacts.

All tools leverage a cosine similarity approach where the user query is first transformed into embeddings that are then compared to those stored in the nodes of the database. In order to optimize the system's efficiency, indexes have been created in the database, pre-calculating the cosine distances between embeddings.

Figure 13 represents a 2D visualization of the embedding space, obtained using UMAP and PCA techniques (a dimensionality reduction method that preserves the local structure of data), and shows the clusters corresponding to the ISIC categories.

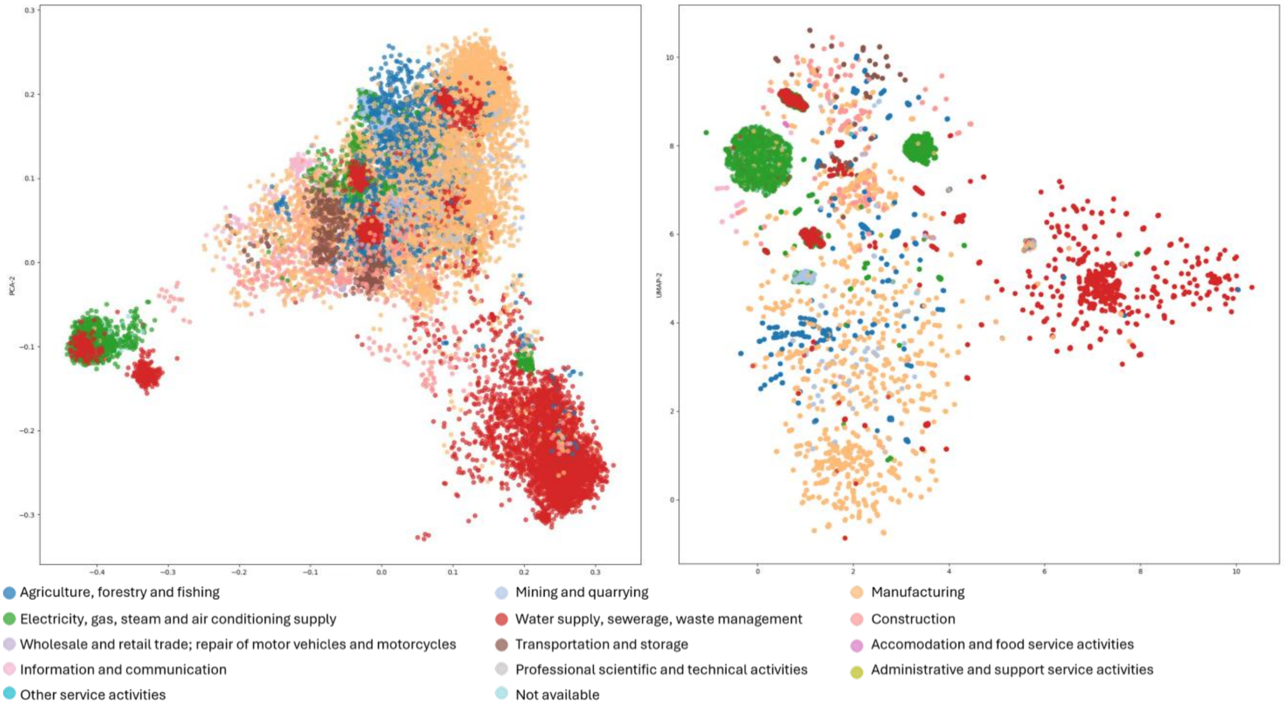


Figure 13 Embedding space 2d visualization

In order to demonstrate the effectiveness of the similarity search agent, different prompts have been tested. One example being: "*Give me the processes most similar to injection moulding process*"; the table below presents the results ranked by cosine similarity (0 means best match). In this case the Agent Supervisor selected the Process/Product description similarity, and the results can be grouped in three different blocks: The top group, "*Injection Moulding and Transport*", includes the process itself along with related factors such as geographical market differences and logistics. "*Blow Moulding alternatives and Transport*" and "*Plastic Extrusion alternatives*" representing processes with notable similarities in material use and infrastructure.

Process	Similarity Score	Process group (custom info)
Injection Molding RoW	0	Injection Molding alternatives transport
Injection Molding RER	0	
Injection Molding CA-QC	0	
Market for Injection Molding	0	
Blow Mouding	0.298	Blow Molding alternatives transport
Market for Blow Molding	0.298	

Stretch Blow Moulding	0.469	
Extrusion, plastic pipes	0.475	Plastic Extrusion alternatives
Market for extrusion	0.475	

2.2.1.4 Chatbot for LCA Expert modelling assistance

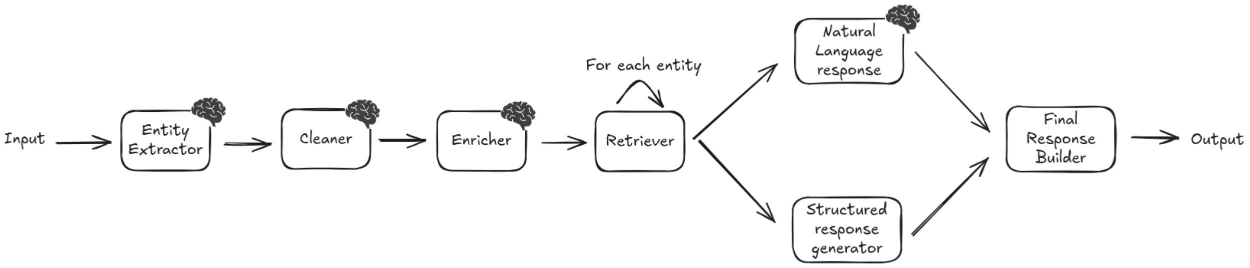
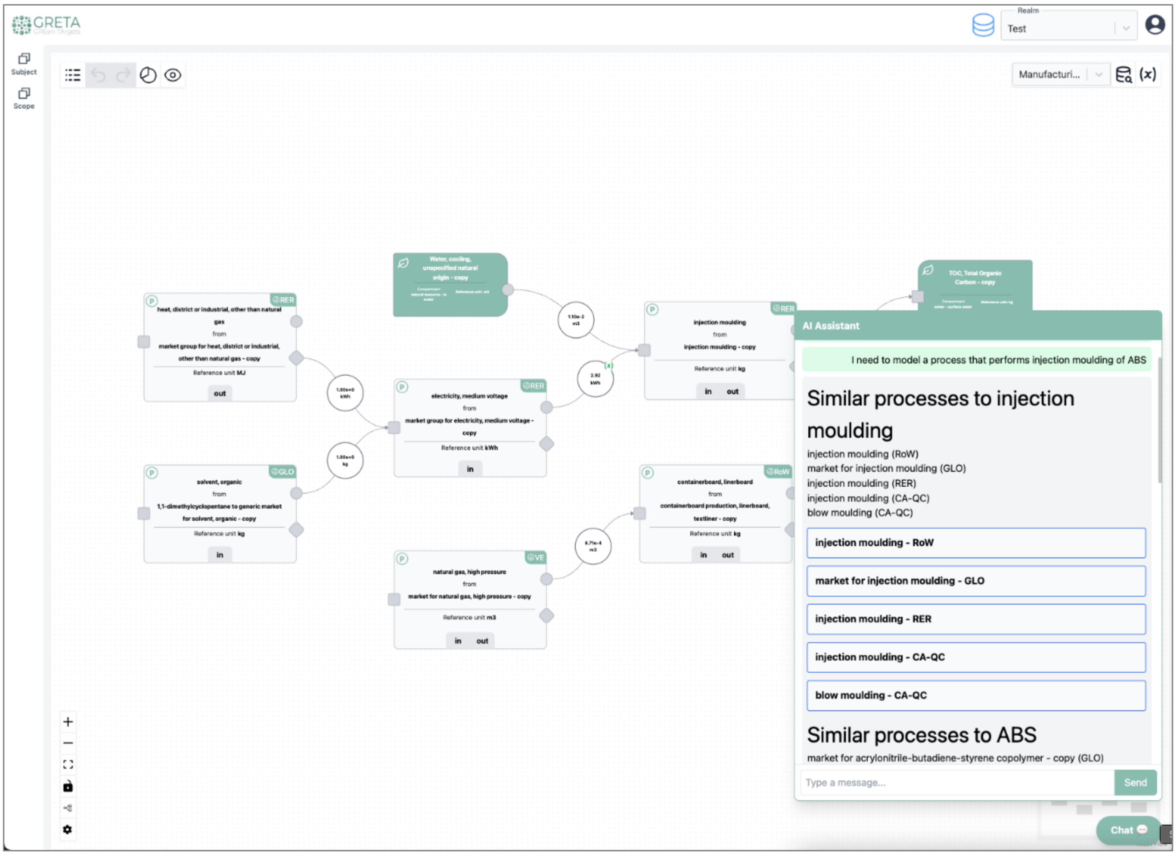


Figure 14 AI workflow behind the sustainability chatbot

The diagram drawn in **Errore. L'origine riferimento non è stata trovata.**, shows an AI workflow which integrates LLM in different steps (those identified by a brain icon) but don't use an LLM to control the workflow execution. Indeed, the sequence of steps is predefined and must be executed in the following order to meet the experts' goals:

- **Entity Extractor**: this task exploits LLM capabilities to extract entities implicit in the users' query like processes, materials, transportation, electricity mixes, and other sustainability-related entities.
- **Cleaner**: this task exploits LLM capabilities to clean the entities extracted in the previous step removing duplicates and expanding acronyms (for example "ABS" becomes "*Acrylonitrile Butadiene Styrene*").
- **Enricher**: this task exploits LLM capabilities to enrich and contextualize the entities giving a description of the entities that needs to be searched in a sustainability database.
- **Retriever**: for each entity, the retriever searches the *similar* entities in a graph database which contains also the entity-related *embeddings* of the product information (a field that resume the description/characteristics of the process/entity). The retriever uses the ***cosine-similarity*** function in order to determine which embedding are the most similar to those used in the user's query. The retrieved entities are called documents.
- Once performed the retrieving, two different steps are executed in parallel:
    - **Natural language response**: this task exploits LLM capabilities to generate a human readable response based on user query and retrieved documents.
    - **Structured response generator**: this task transforms the retrieved documents into machine-readable DTOs.
- **Final response builder**: this task composes the final response mixing together the one produced by the previous two tasks.

This AI workflow has been wrapped in a suite of web-based microservices made available by a set of REST APIs used by a sustainability chatbot, developed for demonstration purposes. These services can be also exploited as a backend service or as a stand-alone advisory, for example for suggesting similar processes to a selected one. As depicted in Figure 15, the sustainability chatbot provided by the GRETA Model Editor is a text area dedicated to managing the messages exchanged between the user (i.e. the questions) and the AI workflow.



I need to model a process that performs injection moulding of ABS

Similar processes to injection moulding

injection moulding (RoW)
market for injection moulding (GLO)
injection moulding (RER)
injection moulding (CA-QC)
blow moulding (CA-QC)

injection moulding - RoW

market for injection moulding - GLO

injection moulding - RER

injection moulding - CA-QC

blow moulding - CA-QC

Similar processes to ABS

market for acrylonitrile-butadiene-styrene copolymer - copy (GLO)

Type a message...

Figure 15 Sustainability chatbot in the GRETA Model Editor

In order to demonstrate the goodness of the developed system, in terms of quality and response times, a list of questions have been tested (the most interesting ones have been reported in ANNEX 1). A larger and more comprehensive test will be conducted in the coming months involving processes and products from the project pilots, which results will be described within D4.2. As shown in the examples, the responses obtained from the AI workflow have a well-defined JSON structure that allows the sustainability chatbot to interpret the results and display them in an "augmented" mode through which the list of the similar entities can be enhanced by a set of functionalities useful to support the user and speed up the modelling phase. For example, the user may be interested in applying the chatbot’s suggestions directly into his model, drag and dropping the similar entities.

```
{
  "similar_entities": [
    {
      "name": "market for injection moulding",
      "id": "342912ff-1cb5-5352-8630-b5585…",
      "refId": "68d6dfcf-2089-4586-9b…",
      "location": {"shortName": "GLO", "id": "34dbbff8-88ce-11d…"},
      "referenceFlow": {"name": "injection moulding"},
      "metadata":{"similarity_score": 0.9279427528381348, "info": ""}
    },
    …
  ]
}
```

Figure 16 Similar Entity Structure

As shown in Figure 16, each similar entity is composed by a set of parameters that helps the sustainability chatbot to create the result in a more user-readable format:

- `Name`: name of process, belonging to the original sustainability database (like ecoinvent or EPD), recognized by the AI workflow
- `Id`: id of the process stored in the GRETA graph database
- `RefId`*:* reference id of the process stored in the original sustainability database (like ecoinvent or EPD)
- `Location`: location where the process is provided
- `ReferenceFlow`: output of the selected process
- `Metadata`: set of further attributes useful to describe the similarity result

2.2.2 GRETA Integration API(s)

As introduced before, GRETA provides an integration layer through which a set of services have been made available through a suite of REST APIs, safeguarded by a security layer controlling access. Such layer of web services allows third-party applications to exploit the GRETA functionalities, from the creation of a new scenario (product alternative) till to the execution of all types of sustainability assessment.

The following tables are meant to describe the list of APIs exposed by GRETA where each API will be presented with a short description, the URL, the HTTP call method, any parameters, a list of any errors, an example of a CURL request and any payload.

PROJECT CREATION	
Description: this API allows the creation of a new project given a `name` and a `description`. The project is like a folder that contains multiple scenarios.	
URL: `/api/v1/project`	*http://<GRETA>/api/v1/project*
Method: `POST`	
URL Params: `none`	
Success response: `200`	
`200` **Response content:**	*Request was successful*

```
{
    "created":"2024-0222T13:38:32.862665476Z",
    "createdBy": "6336334b-c90d-4d5a-989b-5854277fe05d",
    "description": "Project Description",
    "id": "41ba5aa3-be08-4cb6-bc6c-bfdc5359e9bf",
    "lastUpdated": "2024-02-22T13:38:32.862685927Z",
    "name": "project Name",
    "scenarioCount": null
}
```

Error response: `500`, `401`	
`500`	*Internal Server Error*
`401`	*Unauthorized*
Example of CURL request:	

```
curl --location 'http://<GRETA>/api/v1/project' \
```

```
--header 'Content-Type: application/json' \
--header 'Authorization: Bearer ...' \
--data '{
    "id": "",
    "name": "Test",
    "description": "test description"
}'
```

Payload for POST request body:

```
{
   "id":"",
   "name":"Test",
   "description":"test description"
}
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

SCENARIO CREATION

Description: this API allows the creation of a new scenario based on a specified scenario Template, a name, a description and the `projectId` related to a project which must already exist.

URL: `/api/v1/scenario`	*http://<GRETA>/api/v1/scenario*
Method: `POST`	
URL Params: `none`	
Success response: `200`	

`200`

Response content:

```
{
    "created": "2024-02-22T13:39:04.227735697Z",
    "createdBy": "408cf4e7-8b33-4a2e-9ae9-9b7b75b79ade",
    "description": "Scenario description",
    "id": "b850976d-cf5d-4996-b76c-de41a76fc55c",
    "lastUpdated": "2024-02-22T13:39:04.227772578Z",
    "name": "Scenario name",
    "projectId": "2d2b17df-5370-4a12-a6f7-c1ce2281972d",
    "scenarioTemplateId": "65d61e369135ba79b7544814",
    "tags": []
}
```

Request was successful

Error response: `500`, `401`

`500`	*Internal Server Error*
`401`	*Unauthorized*

Example of CURL request:

```
curl --location 'http://<GRETA>/api/v1/scenario' \
--header 'Content-Type: application/json' \
--header 'Authorization: Bearer ...' \
--data '{
    "name": "Demo",
    "id": "",
    "projectId": "a133c678-db9f-406d-8f2b-f33b579d9954",
    "scenarioTemplateId": "65cf1f55edd4034cfcd4628a",
    "tags": [],
    "description": "Demo desc"
}'
```

Payload for POST request body:

```
{
   "name": "Test",
   "id":"",
   "projectId":"a133c678-db9f-406d-8f2b-f33b579d9953",
   "scenarioTemplateId":"65cf1f55edd4034cfcd46282",
   "tags": [
      {id: "be431452-de80-4ad6-819f-284ecbaa49f8"}
   ],
   "description": "Test description"
}
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

GET PHASES

Description: This API will respond with all the defined phases.

URL: `/api/v1/phase`	*http://<GRETA>/api/v1/phase*

Method: `GET`

URL Params: `none`

Success response: `200`

`200`

Response content:

```
[
  {
    "id": "d8fd6490-b982-4157-98ba-cbb1e75cd070",
    "name": "Manufacturing",
    "description": "Manufacturing",
    "color": "#f6d183",
    "created": "2023-10-20T15:02:08.570168Z",
    "lastUpdated": "2024-07-10T07:45:50.054837Z",
    "createdBy": "7944fb06-7256-45a7-b0a2-62b8a8b7ce57",
    "displayOrder": 0
  },
  ...
]
```

Request was successful

Error response: `500`, `401`

`500`	*Internal Server Error*
`401`	*Unauthorized*

Example of CURL request:

```
curl --location 'http://<GRETA>/api/v1/phase' \
--header 'Authorization: Bearer ...'
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

GET SCENARIO CUSTOMIZATION

Description: given a `scenarioId`, this API aims to gather the parameters customization (list of parameters and their values) of the related scenario.

URL: `/api/v1/customized-process/`	*http://<GRETA>/api/v1/customized-process/*

Method: GET

URL Params: scenarioId

scenarioId	*The ID of the scenario for which the customization is required*

Success response: 200

200

Response content (truncated for example purpose):

```
{
    "created": "2024-02-16T08:43:36.510000+0000",
    "lastUpdated": "2024-02-22T10:03:31.917000+0000",
    "createdBy": "83457779-ab97-4e56-b0fb-71801f56a1d7",
    "realm": "test",
    "id": {
        "timestamp": 1708073016,
        "date": "2024-02-16T08:43:36.000+00:00"
    },
    "refId": "21fad086-514b-443e-9954-933c89958661",
    "customization": {
        "parameters": [
            {
                "parameterName": "electricity_mix_assembly",
                "parameterType": "OPTION",
                "unitOfMeasure": null,
                "value": "05aa5-f931-489c-beee-325f3808b686",
            },
             …
        ]
    }
}
```

Request was successful

Error response: 500, 401

500	*Internal Server Error*
401	*Unauthorized*

Example of CURL request:

```
curl --location 'http://<GRETA>/api/v1/customized-process/e7621be0-8725-4065-a198-
03b241966e87' \
--header 'Authorization: Bearer ...'
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

SUSTAINABILITY ASSESSMENT CALCULATION (without payload, with scenario ID)

Description: given a scenarioId, this API calculates the *sustainability impacts* of the specified scenario. The assessment result is organized by *assessment type* (LCA, LCC, SLCA and CE) and it follows the *sustainability methodology* specified in the related scenario template(s).

URL: /api/v1/[bom/basic]/calculate-scenario	*http://<GRETA>/api/v1/bom/calculate-scenario*

Method: POST

URL Params: scenarioId

scenarioId	*The ID of the scenario that wants to be calculated*

`componentsOnly`	*Boolean flag: set it to true to get impacts only for the components in the Bill of Materials (BoM). Impacts from subprocesses will be excluded.*

Success response: `200`

`200`

Response content (truncated for example purpose):

```
[
    {
        "assessmentType": "LCA",
        "phaseResults": [
            {
                "nodeImpactResult": {
                    "children": [
                       …
                    ],
                    "impactList": [
                        {
                            "percentage": 100.00,
                            "selfImpact": -1.2619045E-6,
                            "unit": "kg P-Eq",
                            "value": 0.0020714450245917426
                        },
                        …
                    ],
                    "item": false,
                    "name": "Manufacturing",
                },
                "phaseId":"df6490-b982-4157-98ba-cbcd170"
            }
        ],
        …
    }
]
```

Request was successful

Error response: `500`, `401`

`500`	*Internal Server Error*
`401`	*Unauthorized*

Example of CURL request:

```
curl --location --request POST 'http://<GRETA>/api/v1/basic/calculate-
scenario?scenarioId=e7621be0-8725-4065-a178-03b241966e84&componentsOnly=true' \
--header 'Authorization: Bearer ...'
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

SUSTAINABILITY ASSESSMENT CALCULATION (with payload)

Description: given an object which represents a *customized scenario*, this API calculates its *sustainability impacts*. The assessment result is organized by *assessment type* (LCA, LCC, SLCA and CE) and it follows the *sustainability methodology* specified in the related scenario template(s). This API calculates impacts starting from a customization and not from a scenarioId.

URL: `/api/v1/[bom/basic]/calculate-scenario-with-payload`	*http://<GRETA>/api/v1/[bom/basic]/calculate-scenario-with payload*

Method: `POST`

URL Params: none

Success response: 200

200

Response content (truncated for example purpose):

```
[
    {
        "assessmentType": "LCC",
        "phaseResults": [
            {
                "nodeImpactResult": {
                    "children": [
                       …
                    ],
                    "impactList": [
                        {
                            "percentage": 100.00,
                            "selfImpact": 0.0,
                            "unit": "EUR",
                            "value": 17.5
                        },
                        …
                    ],
                    "item": false,
                    "name": "Manufacturing",
                    "refId": "4027653"
                },
                "phaseId": "6490-b982-4157-98ba-cbb1e75cd070"
            }
        ]
    }
]
```

Request was successful

Error response: 500, 401

500	*Internal Server Error*
401	*Unauthorized*

Example of CURL request (partially truncated for example purpose):

```
curl --location 'http://<GRETA>/api/v1/basic/calculate-scenario-with-payload' \
--header 'Content-Type: application/json' \
--header 'Authorization: Bearer ...' \
--data '{
    "parameters": [
        {
            "alias": "Material",
            "description": null,
            "options": [
                  …
            ],
            "parameterName": "material_production",
            "parameterType": "OPTION",
            "unitOfMeasure": null,
            "validations": null,
            "value": "2c9cfce1-da81-4c4a-8657-0f79e1069e81"
        },
        …
    ]
...
}'
```

Payload for POST request body (truncated for example purpose):

```
{
   "parameters": [
         "parameterName": "electricity_mix_assembly",
         "parameterType": "OPTION",
         "unitOfMeasure": null,
         "validations": null,
         "value":"05aa578b-f931-489c-beee-325f3806b686",
         "index":0
      },
      …
   ]
}
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

HOTSPOT IDENTIFICATION ADVISORY

Description: this API detect which items, phases, or parameters have the highest environmental impact of a product life cycle, specifying its `scenarioId`. Users can prioritize their sustainability efforts by identifying the hotspots addressing resources toward changes that will yield the most substantial improvements. This targeted approach enhances the efficiency and effectiveness of sustainability initiatives.

URL: `/api/v1/bom/calculate-bom-hot-spots`	*http://<GRETA>/api/v1/bom/calculate-bom-hot-spots*

Method: `POST`

URL Params: `scenarioId, thresholdPercentage, indicators`

Success response: `200`

`200`

Response content:

```
{
    "hotspots": [
        "02149sf9-1319-46f9-8fb6-4dft6d8xc359",
        "100005",
        "PCB_WEIGHT:root:100001:100005"
    ]
}
```

Request was successful

Error response: `500`, `401`

`500`	*Internal Server Error*
`401`	*Unauthorized*

Example of CURL request (partially truncated for example purpose):

```
curl --location --request POST 'https://greta/api/v1/bom/calculate-bom-hot-
spots?scenarioId=...&thresholdPercentage=80&indicators=' \
--header 'Authorization: Bearer ...' \
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

BEST CUSTOMIZATION ADVISORY

Description: this API focuses on optimizing production process parameters of a given scenario with the aim to reach a balance between minimizing environmental impact and reducing production costs. It uses a parameter optimization algorithm that considers production constraints defined by sustainability experts within GRETA.

URL: `/api/v1/bom/calculate-bom-hot-spots`	*http://<GRETA>/api/v1/bom/calculate-bom-hot-spots*
Method: `POST`	
URL Params: `algorithm, scenario_id, number_of_scenarios, sustainability_percentage, profit_percentage, indicators, scenario_title, scenario_description`	
Success response: `200`	
`200` **Response content:** `None`	*Request was successful*
Error response: `500`, `401`	
`500`	*Internal Server Error*
`401`	*Unauthorized*
Example of CURL request (partially truncated for example purpose):	

```
curl --location --request POST 'https://greta/api/v1/smos/execute-optimization?algorithm=binary&scenario_id=&number_of_scenarios=1&sustainability_percentage=100&profit_percentage=0&indicators=&scenario_title=&scenario_description=' \
--header 'Authorization: Bearer .... \
```

Notes: this endpoint is **authenticated**. It requires an authentication **token** in the HTTP header.

2.3 Revised Features

2.3.1 Material Circularity Indicator (MCI)

GRETA also provides an engine for calculating circular economy aspects. This engine is the result of a joint development of various indicators, each of which responds to different needs in the various projects where these aspects are assessed.

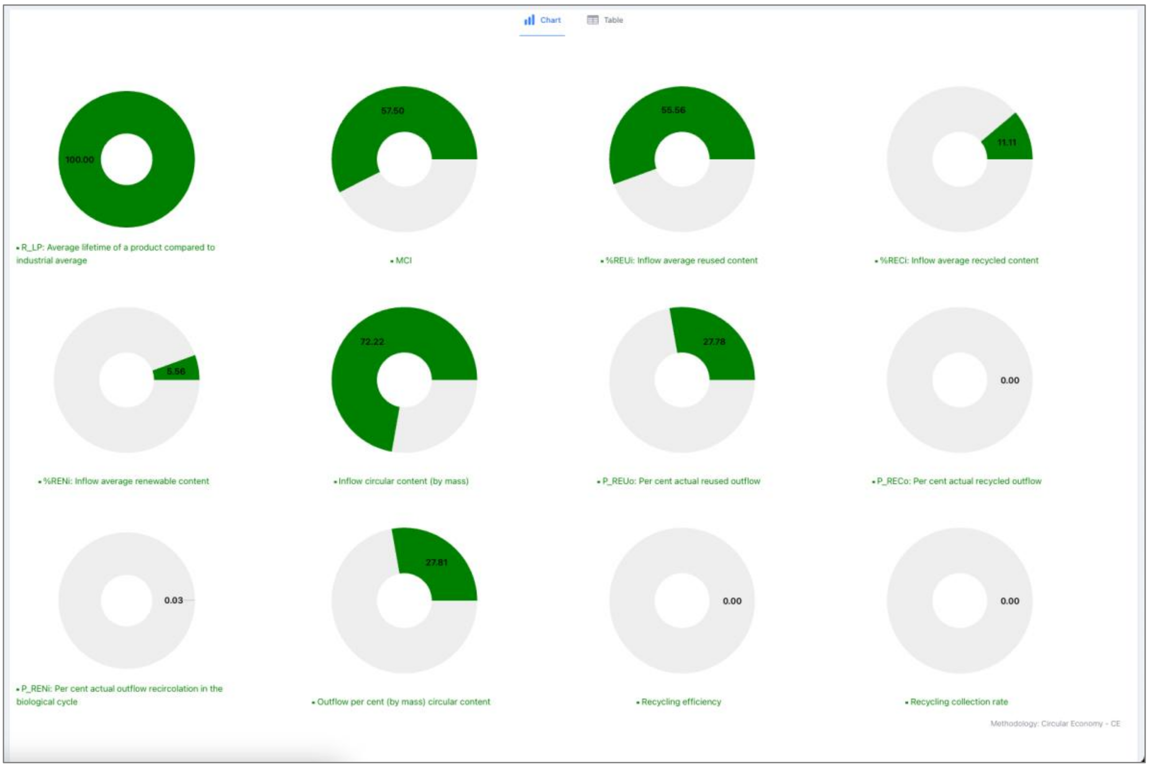


Figure 17 Circular Economy Assessment Dashboard

For the CIRC UITS project, the Material Circularity Indicator (MCI) was selected and tested as the most relevant circularity metric for several pilots. This choice was based on the feedback collected during co creation workshops with the pilot partners, where MCI emerged as the most valuable indicator to support the evaluation of circular design strategies and product performance. In parallel, other indicators more specifically related to recycling were calculated by MARAS through its dedicated recycling simulations, which complemented the broader circularity assessment with detailed End of Life insights. OFFIS, on the other hand, focused on repairability assessment and contributed to the calculation of specific repairability indices, enriching the circularity analysis with aspects related to product maintainability and life extension strategies.

The MCI implementation in GRETA allows for two configuration modes. Users can either manually enter the required values through a dedicated data entry interface, or—when available—an LCA expert can link the MCI inputs directly to the parameters already defined in the life cycle model. This option ensures consistency between the circularity indicator and the inventory data used for the environmental assessment, reducing redundancy and improving accuracy.

The MCI methodology applied in GRETA is based on the definition provided in Deliverable D3.1, and includes key input variables such as feedstock origin, waste generation, recovery rates, and product lifespan. These parameters are processed to compute metrics such as the Linear Flow Index (LFI), the MCI value, and intermediate functional transformations.

This feature demonstrates once more the GRETA ability to support circularity assessments in a modular and user adaptable way, reinforcing its applicability across a variety of industrial contexts and data readiness levels.

3. Validation of Functionalities through CIRC-UITS Pilots

3.1 Modelling Approach for Pilot Validation

The modelling approach adopted for the validation of the CIRCUITS pilots was built upon the methodological framework and indicators defined in the previous deliverable D3.1, which established the structure for integrated Life Cycle Sustainability and Circularity Assessment (LCS&CA). This general methodology was then applicatively implemented in three CIRCUITS pilots: Pilot 1 (Bosch, Electronic Control Unit), Pilot 2 (Continental, Tyre Sensor), and Pilot 3 (TNO, In-Mold Electronics).

Each pilot provided a detailed Bill of Materials (BoM) for their reference product. These BoMs served as the foundation for the life cycle models developed in OpenLCA. Primary data from the BoMs, including material types, quantities, and mass, were integrated with secondary data from established databases such as Ecoinvent and SOCA to build complete product systems covering raw materials, manufacturing processes, and end-of-life scenarios.

Alternative flows were also modelled to simulate different design or sourcing configurations. For example, in Pilot 1, alternative scenarios were created to evaluate the substitution of standard plastics with recycled-content materials or to assess the impact of different electricity mixes in manufacturing processes.

For all three pilots, the LCS&CA functional unit was defined as a single product unit. This choice ensured consistency across the assessments and allowed for comparative analysis of different design options and scenarios within the same pilot.

The resulting models were then imported and configured in GRETA by an LCA expert to ensure consistency, completeness, and usability. Demo accounts were provided to the decision-makers within each pilot organization, enabling them to interact with the models, adjust key product design parameters, and compare sustainability performance across alternative scenarios using GRETA’s scenario comparison and advisory modules.

Each pilot adopted different modules within GRETA depending on their objectives. Pilot 1 focused on LCA; Pilot 2 employed LCA, LCC, SLCA, and the Material Circularity Indicator (MCI); while Pilot 3 applied LCA in conjunction with social and economic.

The following chapters 3.1.1, 3.1.2 and 3.1.3 highlight the specific modelling choices made for each pilot, including decisions on system boundaries, level of detail, and the configuration of alternatives, reflecting the unique priorities and contexts of each industrial case. The objective of this deliverable is to present the LCSA models prepared in GRETA, together with an overall presentation of the draft assessment results obtained. On the contrary, D4.2 at the end of the project will present a more detailed dissertation on the LCSAs that will be refined via the interaction with pilots partners.

3.1.1 Pilot 1: Bosch Life Cycle Modelling Approach, Pilot-Specific Requirements

The Bosch pilot aims to assess the environmental improvements of a “Green ECU” concept by comparing it to the current ECU design in use. In collaboration with the pilot leads, a life cycle assessment (LCA) was performed covering the entire life cycle of the product, from raw material extraction to end-of-life, integrating not only production-phase impacts but also recycling simulation results provided by Maras.

The assessment is based on the confidential bill of materials (BOM) supplied by Bosch and includes all substances that account for at least 90 percent of the total product mass, in addition to all materials classified as Critical Raw Materials (CRMs). This selection ensures that the model captures the most relevant contributors to environmental impact while maintaining focus and transparency.

The methodological framework follows the structure described in Paragraph 3.1 with the following key adaptations. Since the Bosch study focuses exclusively on environmental indicators, the inventory data is based on ecoinvent v3.9.1. In cases where representative datasets were not available in ecoinvent, particularly for specific CRMs such as Germanium, Palladium, and rare earth elements, peer-reviewed literature data was used and is fully documented in the model metadata.

Special attention was given to the printed circuit board (PCB), identified as a major environmental hotspot. Instead of using ecoinvent generic “mounted PCB” datasets, the SUPSI team developed a custom model that accurately reflects the Bosch BOM. The process began with an unpopulated six-layer FR-4 PCB, aligned with Bosch’s specifications in terms of thickness, copper content, and surface area. The board was then populated with exactly two diodes and one integrated circuit, as indicated in the BOM. Each component was individually modelled using dedicated datasets that cover raw material extraction, semiconductor manufacturing, packaging, and soldering with a lead-based paste. This detailed approach enables precise tracking of component-level contributions and avoids double counting of solder and energy already embedded in generic datasets.

The current ECU configuration was fully implemented in GRETA to serve as the baseline for all selected impact categories. The Green ECU configuration was then developed by introducing controlled variations, enabling a structured comparison of different design and supply chain options. Key parameters explored in the scenario analysis include:

- Integration of recycling simulation results from Maras to reflect improved post-consumer material recovery.
- Use of alternative material sourcing, such as recycled-content PBT for the housing cover.
- Substitution of solder paste formulations.
- Application of different electricity mixes for energy-intensive processes, including injection moulding and wave soldering.

By parameterizing these elements in GRETA, the model enables a transparent and scenario-based comparison between the current and improved ECU designs, helping identify the most impactful design and supply chain improvements.

Application of the LCS&CA GRETA Module

Within GRETA, the ECU is structured as a four-level assembly: Level 1 – Circuit (PCB with three SMD components: two diodes and one integrated circuit), Level 2 – Body (Circuit embedded in the injection-moulded frame), Level 3 – Housing (Body enclosed by the injection-moulded cover), and the final product – ECU (Housing completed with externally sourced solenoids). Selecting the:

- ECU node allows the user to customize energy consumption for assembly and disassembly stages and assign the appropriate electricity mix, while each underlying component has dedicated forms for raw material extraction and manufacturing.
- Solenoids (outsourced): quantity, core and wire materials, and winding parameters can be customized.
- Cover and frame (in-house): polymer-to-glass-fibre ratios, recycled or non-recycled feedstock content, and injection moulding parameters are configurable.
- PCB (outsourced): board type, lead content, mounting technology, soldering energy, and paste composition can be defined.
- Comp 1–3 (outsourced SMD components): material composition and package mass of the two diodes and the integrated circuit follow the same input scheme as the other components.

Any changes are immediately reflected in the bill of materials, ensuring consistency in the life cycle inventory across all assembly levels. Figure 18 shows the BOM of the Bosch ECU in GRETA.

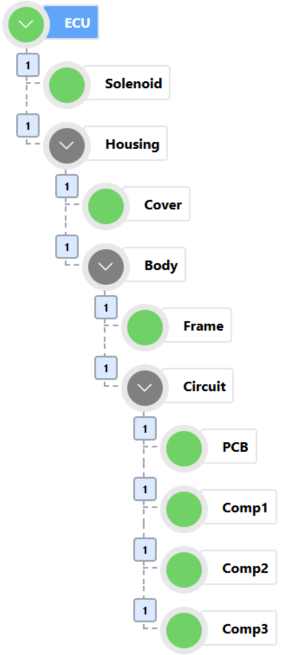


Figure 18: Bill of Materials of the Bosch ECU in GRETA

The LCA model currently includes the following life cycle phases:

- *Raw Material Extraction*, covering the sourcing and transformation of input materials used in the various components, including metals, polymers, and critical raw materials
- *Manufacturing*, representing the production processes of individual components, such as PCB fabrication, plastic injection moulding, and soldering
- *Assembly*, referring to the integration of all components into the final product (ECU), including frame closure and connection of external parts
- *Disassembly*, simulating the operations required to separate the final ECU into its main subassemblies at the end of use.

The *End of Life* phase is not yet included in the GRETA model but is being developed using data provided by MARAS from their recycling simulations. This phase has so far been modelled within OpenLCA and will be integrated into GRETA in the final version of the model.

Once the configuration is complete, the assessment can be launched. The tool will rapidly calculate the values for all impact indicators included in the LCA EF 3.1 methodology. Results are displayed in bar chart, table, and BOM view, with contributions broken down by life cycle stages: Raw Material Extraction, Manufacturing, Assembly, and Disassembly. Figure 19 shows the contribution of each phase (Raw Material Extraction, Manufacturing, Assembly, Disassembly) to the overall environmental impact of the ECU.

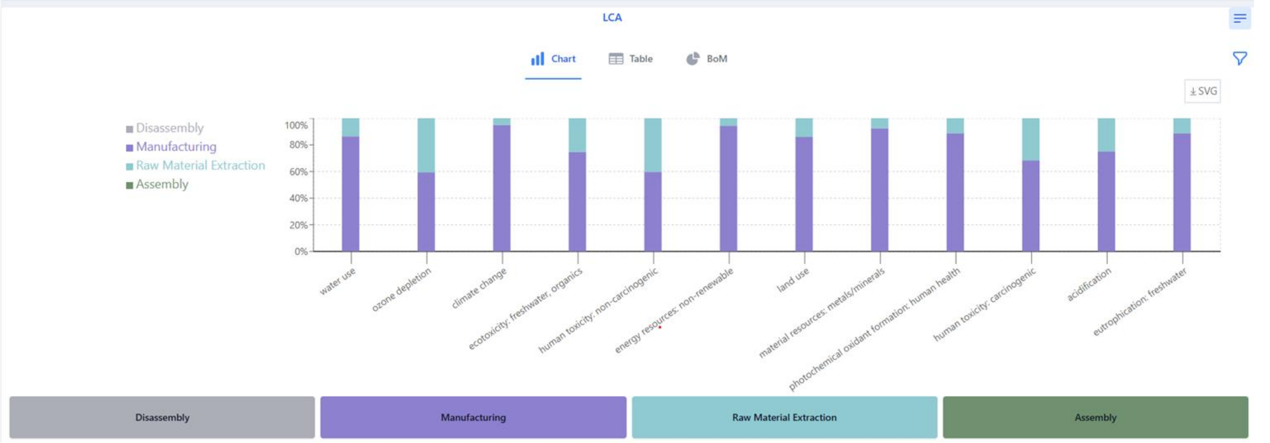


Figure 19 Bosch: Environmental impact distribution across life cycle stages

Figure 20 shows the environmental impact contribution of each component, disaggregated by life cycle phase (Raw Material Extraction, Manufacturing, Assembly, Disassembly). The chart allows the user to select one or more impact indicators (up to four) to be displayed simultaneously. Color coding distinguishes the contribution of each phase for every component. In this example, the selected indicator is "Climate Change – Global Warming Potential (GWP100)". The chart highlights that the manufacturing phase of the PCB is the main contributor to the overall climate change impact of the ECU.

Figure 20 Bosch: Component-level environmental impact breakdown across life cycle phases

The validation work of GRETA's services with the Bosch pilot concludes at this stage. All results, based on the updated model including the End-of-Life phase and primary data from Alpha, and the validation of advisory services, will be presented and discussed in detail in Deliverable D4.2.

3.1.2 Pilot 2: Life Cycle Modelling Approach, Pilot-Specific Requirements

The Continental pilot aims to evaluate the potential environmental improvements introduced by two innovative TPMS (Tire Pressure Monitoring System) concepts, the Badge and Cage, in comparison to the current system in use. This initiative is part of Continental's commitment to sustainable innovation within the CIRC-UITs project, which promotes circular design strategies aimed at achieving carbon neutrality.

In collaboration with Continental, a life cycle assessment (LCA) was carried out. The LCA covers the entire product life cycle, from raw material extraction to end of life, integrating both the production phase and the recycling potential of components, recycling scenarios were developed by Maras.

The LCA was conducted using the confidential bill of materials (BOM) shared by Continental. This BOM includes data for each component, such as material type and mass, which were essential to quantify impacts across all life cycle phases. In addition to the LCA, for this pilot also the Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA) and the Material Circularity Indicator (MCI) have been calculated.

The methodological framework adheres to the structure outlined in Paragraph 3.1. Although both the Badge and Cage concepts are included in the scope of the pilot, the current analysis has been conducted exclusively on the Cage model. The analysis of the Badge concept is planned as a next step, to enable a comparative assessment between the two designs and better inform future design and sustainability decisions.

Application of the LCS&CA GRETA Module

Within the GRETA platform, the Cage concept is organized as illustrated in the corresponding Figure 21.

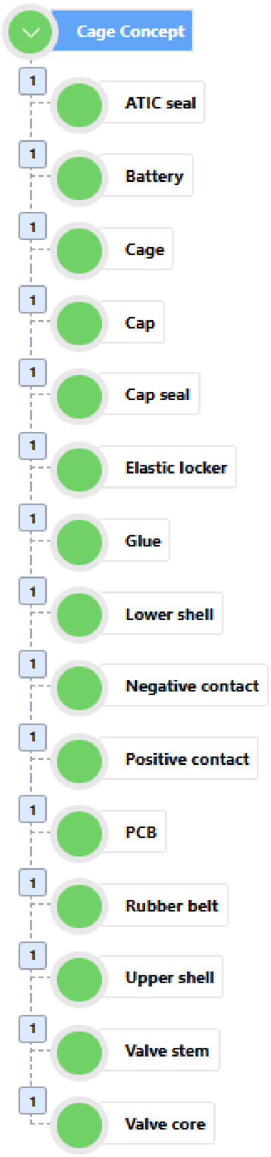


Figure 21: Bill of Materials of the Continental Reference Product in GRETA

The Figure 21 presents the Bill of Materials (BOM) structure for the Cage design in GRETA. The hierarchy is organized over two levels: the first level corresponds to the main product, the Cage itself, while the second level details all the individual components that constitute the product.

The LCA model implemented encompasses the following life cycle phases:

- *Raw Material Extraction*: includes the sourcing and initial transformation of materials used in the components, such as metals, polymers, and critical raw materials.
- *Manufacturing*: covers production processes specific to each component, including PCB fabrication, plastic injection moulding and metal working.
- *Assembly*: refers to the integration of all components into the final cage.
- *Reuse*: as detailed in Paragraph **Errore. L'origine riferimento non è stata trovata.**.
- *End-of-Life*: considers the environmental impacts associated with the product’s final stage.

As said before for the Bosch’s ECU when the configuration is completed, the assessment can be launched and the tool automatically computes the results across all four dimensions of analysis: Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA), and Material Circularity Indicator (MCI). The outputs are visualized through bar charts, data tables, and a BOM structured view, with impact contributions clearly broken down by life cycle phases.

Figure 22 illustrates the environmental impact distribution across the life cycle stages for the Cage concept. A similar breakdown is provided for the other assessments, LCC and SLCA, allowing for a comprehensive and comparative interpretation of sustainability performance across environmental, economic, social, and circularity dimensions.

Figure 22: CONTINENTAL - Environmental impact distribution across life cycle stages

Once again, it is possible to visualize the environmental impact contribution of each individual component, broken down by life cycle phase. The chart in Figure 23 allows users to identify which components have the highest impacts based on the selected impact categories. In this case, the chart highlights that the manufacturing phase of the PCB is the main contributor to the overall climate change impact of the Cage concept. A similar visualization structure is also available for the SLCA results, enabling users to explore social impacts at component level across different life cycle stages.

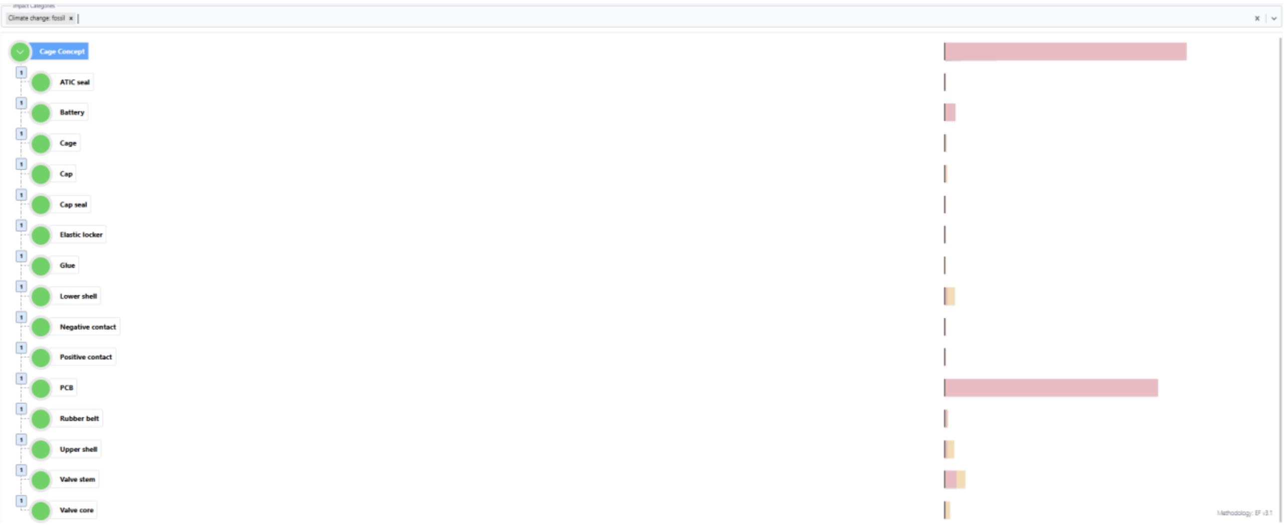

Impact Categories
Climate change: fossil

Figure 23: CONTINENTAL - Component-level environmental impact breakdown across life cycle phases

All results, including the comparison with the Badge concept and the validation of advisory services, will be presented and discussed in detail in Deliverable D4.2.

3.1.3 Pilot 3: TNO Life Cycle Modelling Approach, Pilot-Specific Requirements

The reference product is an In-Mold Electronic (IME) circuit, which consists of a polycarbonate substrate printed with multiple layers of graphic inks and conductive silver ink using screen printing techniques. After printing, electronic components are attached to the surface using conductive adhesives. The assembled circuit is then thermoformed into a 3D shape using a hot molding process.

The final 3D-shaped circuit serves as the functional and structural form of the IME system, integrating both mechanical and electronic functionalities in a single molded piece.

Figure 24: TNO Reference Product

The Life Cycle Assessment (LCA) was developed using a BoM-based modeling approach in OpenLCA. The underlying dataset was derived from a detailed Excel file containing comprehensive information on the material composition, physical properties and process parameters for each component of the E-tile.

Composition Overview

The product is composed of 14 distinct components as shown in Figure 25 each fulfilling a specific functional or structural role within the final product. Since some components appear multiple times across the system, is indicated next to each component name the identification letters used in the modeling to distinguish them where needed. These components are:

A – L. Polycarbonate – Structural Substrate: Polycarbonate is the main mechanical support for the tile, offering excellent transparency, impact resistance, and dimensional stability. This material is extruded into sheets and serves as the foundational layer upon which conductive and decorative layers are printed. Its life cycle includes the synthesis of bisphenol-A, phosgene or diphenyl carbonate, and energy-intensive extrusion.

B – F – H. ME603 – Conductive Ink Layer: ME603 is a silver-based conductive ink, it is applied via screen printing to create electrical pathways on the flexible substrate. This layer enables current flow and connects various functional elements embedded in the tile. The formulation includes finely dispersed silver particles, acting as the primary conductive element, along with solvents such as acetone and a C3 hydrocarbon mixture that help to control viscosity and drying time. Additionally, the base polymer (polycarbonate) is integrated either as a matrix or a substrate material. Once mixed, the ink is applied using screen printing equipment. The drying and curing stages are carried out at controlled temperatures to solidify the layer while retaining flexibility and conductivity.

C – E. Noriphan N2K Weiss – White Protective Ink Layer: This white ink, diluted with 10% thinner, is printed onto the tile surface to provide visual uniformity, UV protection, and mechanical coverage of the underlying circuitry. It is typically composed of acrylic or polyurethane-based resins combined with white pigments (such as titanium dioxide) and a range of organic solvents. In the modeling, this component draws from raw materials linked to resin manufacturing, pigment production, and solvent distillation. The application is done via screen printing, followed by solvent evaporation and film formation.

D. Noriphan N2K Tiefblau – Blue Ink Layer: This layer is functionally similar to the white ink but uses a blue pigment (commonly copper phthalocyanine) to serve aesthetic or coding purposes. Like the white ink, it is printed in thin films and cured thermally. The environmental modeling accounts for the pigment synthesis, binder formulation, and solvent use, all of which contribute to the coating's environmental footprint.

G.Dielectric Layer – Electrical Insulation: Placed between conductive layers, the dielectric layer ensures electrical isolation and prevents short circuits. It is composed of polymer-based formulations, often with a polyurethane or epoxy base, that are applied as thin coatings. This component was modeled with material inputs including base polymers, fillers, and organic solvents. Processing involves dispersion mixing, precision coating, and UV or thermal curing, depending on the chemistry used.

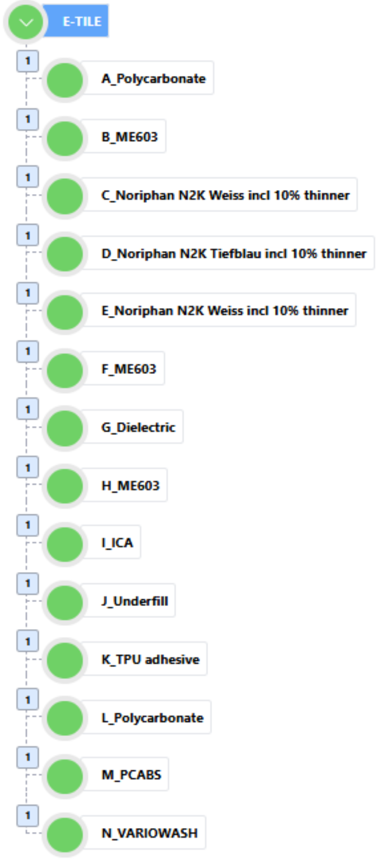
I.ICA – Isotropic Conductive Adhesive: The ICA is a functional adhesive that bonds components while allowing for electrical conduction across contact points. Unlike traditional solder, it allows low-temperature processing and flexibility. Its composition involves silver microparticles suspended in an epoxy matrix. From a life cycle perspective, silver extraction and refining are high-impact processes, while epoxy production and adhesive formulation add chemical complexity. Application involves microdispensing, followed by curing in an oven at moderate temperatures.

J.Underfill – Chip Encapsulation: This component enhances the mechanical stability and thermal dissipation of the e-tile by filling the gap beneath sensitive electronic components. Typically made of epoxy loaded with fine fillers, underfill is dispensed after chip placement and then cured. Its environmental model includes resin production, filler mining (such as silica), and thermal curing processes. It plays a vital role in extending the functional life of the e-tile under thermal or mechanical stress.

K.TPU Adhesive – Lamination Layer: The thermoplastic polyurethane (TPU) adhesive serves as a structural binding layer between components. It is essential for maintaining the mechanical integrity of the multilayer structure, especially in flexible conditions. The adhesive is extruded or applied as a film, then heat-laminated under pressure. Raw materials include TPU granules derived from isocyanates and diols.

M.PC/ABS – Structural Blend Layer: The PC/ABS blend is used where impact resistance and mechanical strength are required. It combines the rigidity of polycarbonate with the processability of ABS. Its production involves co-extrusion of two polymers and the use of compatibilizers. From a life cycle standpoint, both base polymers are derived from petrochemical feedstocks and include polymerization, blending, and compounding processes.

N.VARIOWASH – Cleaning Agent: VarioWash is an industrial cleaning solution, it ensures the removal of contaminants or excess inks, enabling optimal layer adhesion. Its composition includes volatile solvents like methyl ethyl ketone, acetates, and alcohols. Though used in small quantities, the volatility and flammability of its components contribute to its environmental profile.



E-TILE

1 A_Polycarbonate

1 B_ME603

1 C_Noriphan N2K Weiss incl 10% thinner

1 D_Noriphan N2K Tiefblau incl 10% thinner

1 E_Noriphan N2K Weiss incl 10% thinner

1 F_ME603

1 G_Dielectric

1 H_ME603

1 I_ICA

1 J_Underfill

1 K_TPU adhesive

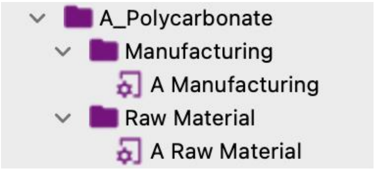
1 L_Polycarbonate

1 M_PCABS

1 N_VARIOWASH

Figure 25: Bill of Materials of the TNO Reference Product in GRETA

For the modeling activity, it has been adopted a BOM (Bill of Materials) approach in OpenLCA in order to enable a structured and consistent transfer of the model into the GRETA. This approach consists in building the LCA model starting from the product's bill of materials—a detailed and hierarchical list of all components and subcomponents. Each main component identified in the BOM has been represented as a separate process in OpenLCA. For each component, its subcomponents and basic materials have been grouped and organized under "Raw Material" folders, while the related transformation and processing activities have been modeled under "Manufacturing" folders as shown in Figure 26 **.**This structure mirrors the physical and functional architecture of the product, ensuring a modular, transparent, and easily maintainable model. The BOM approach also facilitates targeted scenario analyses and future model updates and is particularly suited for integration with digital tools like GRETA.

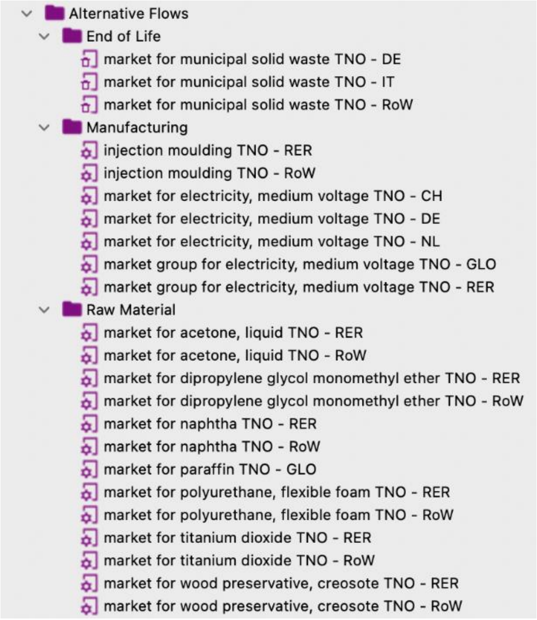


- A_Polycarbonate
  - Manufacturing
    - A Manufacturing
  - Raw Material
    - A Raw Material

Figure 26: IME's BOM modeling in OpenLCA

Subsequently, a *"TNO_E-TILE"* folder was modeled, in which the end-of-life phase of the product is addressed. Given the heterogeneous nature of the subcomponents, a generic disposal scenario was considered to represent the product's end-of-life treatment. It is important to note that no separate assembly phase was included in the model: each component is assumed to be integrated progressively during its respective transformation phase, meaning that the product is fully assembled as a result of the cumulative manufacturing steps, without requiring a distinct final assembly stage.

To fully leverage the comparison capabilities of the GRETA platform and give the possibility to a pilot to simulate different scenarios, a series of alternative flows were modeled within OpenLCA. These alternative scenarios were developed to explore the environmental impact of key variables across the life cycle of the product. Specifically, variations were introduced in terms of the electricity mix used during manufacturing processes, depending on the country of origin. This allows for the assessment of how different national energy profiles (e.g., France, Germany, Italy) affect the overall environmental performance of the system. In addition, where available within the Ecoinvent 3.10 APOS database, alternative sourcing options for certain subcomponents were modeled based on their geographic origin. For instance, materials or parts that could be sourced from multiple countries (e.g., aluminum, glass, or electronic parts) were assigned alternative datasets reflecting country-specific supply chains. These variations were introduced as alternative flows directly linked to the primary product system, allowing GRETA to automatically compare scenarios and quantify the relative impact of geographic and energy-related choices. The Figure 27 shows all the alternative flows modeled for the system. These alternatives are organized by life cycle phase, allowing a clear view of how different options have been modeled across the product system. It can be observed that, for the same subcomponent or process, multiple alternatives are included based on the country of origin, reflecting variations in electricity mix, supply chains, or production conditions.



- Alternative Flows
  - End of Life
    - market for municipal solid waste TNO - DE
    - market for municipal solid waste TNO - IT
    - market for municipal solid waste TNO - RoW
  - Manufacturing
    - injection moulding TNO - RER
    - injection moulding TNO - RoW
    - market for electricity, medium voltage TNO - CH
    - market for electricity, medium voltage TNO - DE
    - market for electricity, medium voltage TNO - NL
    - market group for electricity, medium voltage TNO - GLO
    - market group for electricity, medium voltage TNO - RER
  - Raw Material
    - market for acetone, liquid TNO - RER
    - market for acetone, liquid TNO - RoW
    - market for dipropylene glycol monomethyl ether TNO - RER
    - market for dipropylene glycol monomethyl ether TNO - RoW
    - market for naphtha TNO - RER
    - market for naphtha TNO - RoW
    - market for paraffin TNO - GLO
    - market for polyurethane, flexible foam TNO - RER
    - market for polyurethane, flexible foam TNO - RoW
    - market for titanium dioxide TNO - RER
    - market for titanium dioxide TNO - RoW
    - market for wood preservative, creosote TNO - RER
    - market for wood preservative, creosote TNO - RoW

Figure 27: TNO - Overview of Alternative Flows Considered

During the modeling phase, it has been implied the SOCA (Social Organizational Capacity Assessment) database, available within OpenLCA, in combination with the Ecoinvent 3.10 APOS inventory database. SOCA was used to systematically incorporate the social dimension into the life cycle model, enabling the association of inventory flows with social risk indicators based on country and sector-specific data. These indicators cover a broad range of social issues, including labor rights, health and safety, fair wages, human rights, and community impacts, thereby providing a qualitative understanding of potential social risks along the supply chain.

In addition to the social perspective, the model was enhanced with economic parameters by assigning indicative cost values to selected materials and processes. These cost estimates, though simplified, allow for a preliminary assessment of the economic implications of different life cycle stages and design choices.

Application of the LCS&CA GRETA Module

As previously mentioned in the previous pilots, once the configuration is finalized, the assessment can be initiated. The tool then automatically calculates the results across four analytical dimensions: Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA). The outcomes are presented using bar charts, data tables, and a Bill of Materials (BOM) structured view, clearly displaying impact contributions by each life cycle phase. Figure 28 illustrates the environmental impact distribution across the life cycle stages for the TNO product reference. A similar breakdown is provided for the other assessments, LCC and SLCA, allowing for a comprehensive and comparative interpretation of sustainability performance across environmental, economic, social, and circularity dimensions.

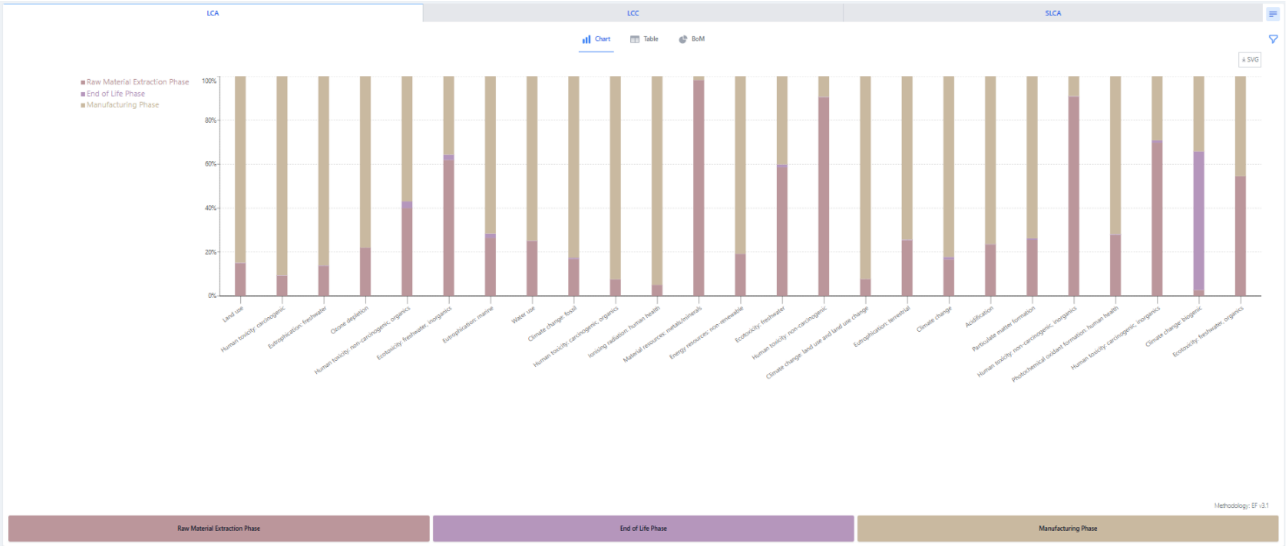
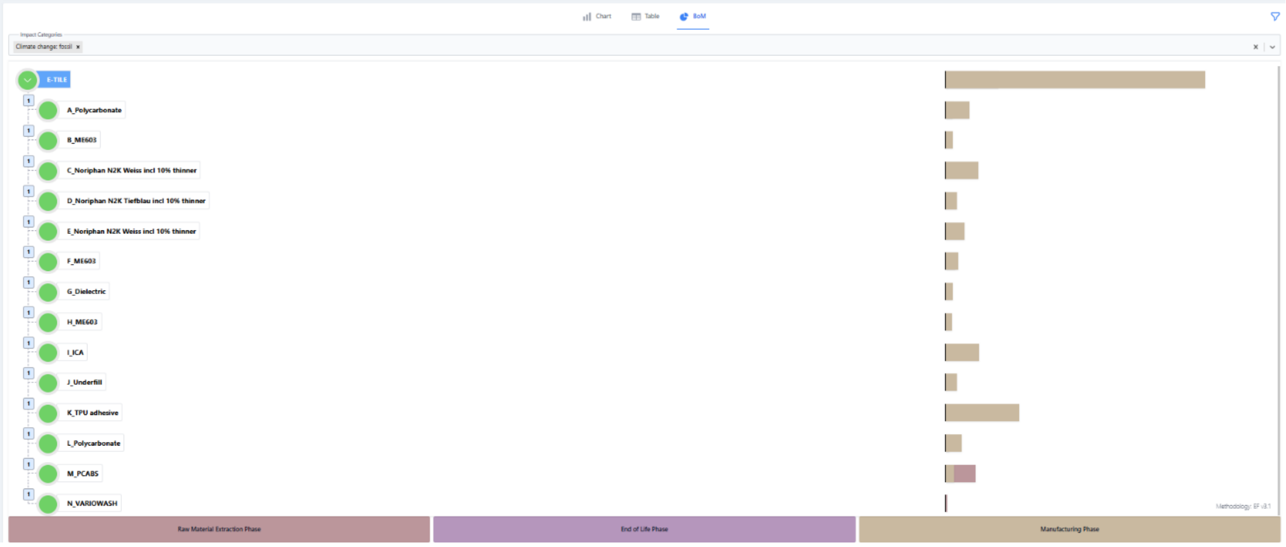


Figure 28: TNO - Environmental impact distribution across life cycle stages

Once again, the tool enables users to examine the environmental impact of each component individually, with contributions detailed by life cycle phase. The chart shown in Figure 29 helps identify which components exert the greatest influence based on the chosen impact categories. In this scenario, it becomes evident that the manufacturing stage of components A – C – I – K are the primary drivers of the overall climate change impact for the product. A comparable visualization format is available for the SLCA results as well, allowing users to analyze social impacts per component across various life cycle stages.



Impact Categories: Climate change: fossil

Figure 29: TNO - Component-level environmental impact breakdown across life cycle phases

The impact results and the validation of advisory services will be presented and discussed in detail in Deliverable D4.2.

3.2 Next steps

While Work Package 3 officially concludes with the delivery of this report, marking the end of the core development phase for the GRETA platform and its integrated services, the work on validation and application is still ongoing. WP3 focused primarily on the design, implementation and initial testing of the GRETA functionalities, ensuring their technical readiness and compatibility with the needs of the project pilots. However, the in-depth analysis and discussion of the Life Cycle Sustainability and Circularity Assessment (LCS&CA) results for each pilot are part of Work Package 4 and will be further refined in the coming months.

Thanks to the strong alignment between WP3 and WP4, the validation activities continue seamlessly. GRETA's functionalities are being used to generate and compare alternative scenarios, with a focus on incorporating the most up to date and pilot specific data. These results will be critically analysed, contextualised through comparison with existing studies, and discussed in detail in Deliverable D4.2, which will provide a comprehensive evaluation of the sustainability performance of the pilot cases.

Ongoing activities include the testing of the Material Circularity Indicator (MCI) in alternative scenarios, with the support of Continental in providing input data through the user interface. In parallel, the Bosch model is being updated with primary data from Alpha, specifically regarding the metallization process and solder pastes, in order to improve the precision of the environmental impact calculation. Additionally, the advisory services are undergoing further validation, with particular attention to the AI based chatbot, which is being evaluated in terms of its effectiveness in assisting LCA experts during the modelling and assessment phases.

These next steps will contribute to consolidating GRETA's role as a robust and adaptable tool for sustainability assessment and will ensure that the final outcomes of the project reflect both technical soundness and real world applicability.

Annexes

ANNEX 1: Examples of user’s queries

Query	**Can you help me assess the environmental impacts of my milling process?**
Answer	

```
{
  "title": "Similar processes to milling process",
  "list": [
    "market for steel removed by milling, dressing (GLO
(0.9067411422729492))",
    "steel milling, dressing (RoW (0.9067411422729492))",
    "steel milling, dressing (RER (0.9067411422729492))",
    "steel milling, small parts (RER (0.9037795066833496))",
    "market for steel removed by milling, small parts (GLO
(0.9037795066833496))"
  ],
  "similar_entities": [
    {
      "name": "market for steel removed by milling, dressing",
      "id": "e75a25fb-e4f0-5cdf-9c6e-5a2…",
      "refId": "2c05646d-138c-4d6c-a33d-99b8e6194328",
      "location": {
        "shortName": "GLO",
        "id": "34dbbff8-88ce-11de-ad60-0019e336be3a"
      },
      "referenceFlow": {
        "name": "steel removed by milling, dressing"
      },
      "metadata": {
        "similarity_score": 0.9067411422729492,
        "info": ""
      }
    },
    {
      "name": "steel milling, dressing",
      "id": "d37bbb6e-1f6b-5023-9f42-cbd5fd862…",
      "refId": "2c05646d-138c-4d6c-a33d-99b8e6194328",
      "location": {
        "shortName": "RoW",
        "id": "7846b897-7c04-4f9f-b607-2b83fcd9a74c"
      },
      "referenceFlow": {
        "name": "steel removed by milling, dressing"
      },
      "metadata": {
        "similarity_score": 0.9067411422729492,
        "info": ""
      }
    },
    {
      "name": "steel milling, dressing",
      "id": "6d55553f-068a-554e-b7b1-a9546509…",
      "refId": "2c05646d-138c-4d6c-a33d-99b8e6194328",
      "location": {
        "shortName": "RER",
        "id": "0723d252-7e2a-11de-9820-0019e336be3a"
      },
      "referenceFlow": {
        "name": "steel removed by milling, dressing"
```

```
      },
      "metadata": {
        "similarity_score": 0.9067411422729492,
        "info": ""
      }
    },
    {
      "name": "steel milling, small parts",
      "id": "2a2c3bfa-2803-5fa1-9547-e0d11e…",
      "refId": "a1de1103-7e58-4fe9-bd26-b86ebd3211b3",
      "location": {
        "shortName": "RER",
        "id": "0723d252-7e2a-11de-9820-0019e336be3a"
      },
      "referenceFlow": {
        "name": "steel removed by milling, small parts"
      },
      "metadata": {
        "similarity_score": 0.9037795066833496,
        "info": ""
      }
    },
    {
      "name": "market for steel removed by milling, small parts",
      "id": "d46610b5-8201-5b22-af9f-a8438d34a…",
      "refId": "a1de1103-7e58-4fe9-bd26-b86ebd3211b3",
      "location": {
        "shortName": "GLO",
        "id": "34dbbff8-88ce-11de-ad60-0019e336be3a"
      },
      "referenceFlow": {
        "name": "steel removed by milling, small parts"
      },
      "metadata": {
        "similarity_score": 0.9037795066833496,
        "info": ""
      }
    }
  ]
}
```

Query	**I need support modeling an injection molding process for ABS material in a European context**

Answer

```
{
  "title": "Similar processes to injection molding",
  "list": [
    "market for injection moulding (GLO (0.9279427528381348))",
    "injection moulding (RER (0.9279427528381348))",
    "injection moulding (CA-QC (0.9278736114501953))",
    "injection moulding (RoW (0.9275569915771484))",
    "market for glass fibre reinforced plastic, polyamide, injection
moulded (GLO (0.8660373687744141))"
  ],
  "similar_entities": [
    {
      "name": "market for injection moulding",
      "id": "342912ff-1cb5-5352-…",
      "refId": "68d6dfcf-2089-4586-9bbf-ad75591105cf",
      "location": {
        "shortName": "GLO",
```

```
        "id": "34dbbff8-88ce-11de-ad60-0019e336be3a"
      },
      "referenceFlow": {
        "name": "injection moulding"
      },
      "metadata": {
        "similarity_score": 0.9279427528381348,
        "info": ""
      }
    },
    {
      "name": "injection moulding",
      "id": "bee2e966-5bf3-53e7-9c7…",
      "refId": "68d6dfcf-2089-4586-9bbf-ad75591105cf",
      "location": {
        "shortName": "RER",
        "id": "0723d252-7e2a-11de-9820-0019e336be3a"
      },
      "referenceFlow": {
        "name": "injection moulding"
      },
      "metadata": {
        "similarity_score": 0.9279427528381348,
        "info": ""
      }
    },
    {
      "name": "injection moulding",
      "id": "d54b935f-486c-5221-9c1…",
      "refId": "68d6dfcf-2089-4586-9bbf-ad75591105cf",
      "location": {
        "shortName": "CA-QC",
        "id": "868a66d1-7428-4ba2-9125-253b07afc119"
      },
      "referenceFlow": {
        "name": "injection moulding"
      },
      "metadata": {
        "similarity_score": 0.9278736114501953,
        "info": ""
      }
    },
    {
      "name": "injection moulding",
      "id": "4efefd5c-012b-5566-b25a-…",
      "refId": "68d6dfcf-2089-4586-9bbf-ad75591105cf",
      "location": {
        "shortName": "RoW",
        "id": "7846b897-7c04-4f9f-b607-2b83fcd9a74c"
      },
      "referenceFlow": {
        "name": "injection moulding"
      },
      "metadata": {
        "similarity_score": 0.9275569915771484,
        "info": ""
      }
    },
    {
      "name": "market for glass fibre reinforced plastic, polyamide,
injection moulded",
```

```
      "id": "455da9e0-b37d-5042-9…",
      "refId": "0798a5d1-6713-4c82-8ec9-c40ac2548279",
      "location": {
        "shortName": "GLO",
        "id": "34dbbff8-88ce-11de-ad60-0019e336be3a"
      },
      "referenceFlow": {
        "name": "glass fibre reinforced plastic, polyamide, injection
moulded"
      },
      "metadata": {
        "similarity_score": 0.8660373687744141,
        "info": ""
      }
    }
  ]
},
{
  "title": "Similar processes to ABS",
  "list": [
    "market for acrylonitrile-butadiene-styrene copolymer (GLO
(0.8853263854980469))",
    "acrylonitrile-butadiene-styrene copolymer production (RER
(0.8853263854980469))",
    "acrylonitrile-butadiene-styrene copolymer production (RoW
(0.8853263854980469))",
    "styrene-acrylonitrile copolymer production (RoW (0.867431640625))",
    "market for polybutadiene (GLO (0.8650093078613281))"
  ],
  "similar_entities": [
    {
      "name": "market for acrylonitrile-butadiene-styrene copolymer",
      "id": "ab6cf858-3cb5-5ed2-bb88…",
      "refId": "71e296f1-2f6d-481a-87ed-e0eac085054d",
      "location": {
        "shortName": "GLO",
        "id": "34dbbff8-88ce-11de-ad60-0019e336be3a"
      },
      "referenceFlow": {
        "name": "acrylonitrile-butadiene-styrene copolymer"
      },
      "metadata": {
        "similarity_score": 0.8853263854980469,
        "info": ""
      }
    },
    {
      "name": "acrylonitrile-butadiene-styrene copolymer production",
      "id": "34048fa3-2a8f-542a-aee8…",
      "refId": "71e296f1-2f6d-481a-87ed-e0eac085054d",
      "location": {
        "shortName": "RER",
        "id": "0723d252-7e2a-11de-9820-0019e336be3a"
      },
      "referenceFlow": {
        "name": "acrylonitrile-butadiene-styrene copolymer"
      },
      "metadata": {
        "similarity_score": 0.8853263854980469,
        "info": ""
      }
```

```
    },
    {
      "name": "acrylonitrile-butadiene-styrene copolymer production",
      "id": "2b75993f-4b72-5ffe-8eb6…",
      "refId": "71e296f1-2f6d-481a-87ed-e0eac085054d",
      "location": {
        "shortName": "RoW",
        "id": "7846b897-7c04-4f9f-b607-2b83fcd9a74c"
      },
      "referenceFlow": {
        "name": "acrylonitrile-butadiene-styrene copolymer"
      },
      "metadata": {
        "similarity_score": 0.8853263854980469,
        "info": ""
      }
    },
    {
      "name": "styrene-acrylonitrile copolymer production",
      "id": "3ff7de57-a9c1-5124-8de…",
      "refId": "7338d72b-9db1-44cd-9047-ad82aa557730",
      "location": {
        "shortName": "RoW",
        "id": "7846b897-7c04-4f9f-b607-2b83fcd9a74c"
      },
      "referenceFlow": {
        "name": "styrene-acrylonitrile copolymer"
      },
      "metadata": {
        "similarity_score": 0.867431640625,
        "info": ""
      }
    },
    {
      "name": "market for polybutadiene",
      "id": "12fcc40b-2dcb-5c00-b9af…",
      "refId": "d6ec2fa7-9885-4c36-afb9-1d336d86c3dd",
      "location": {
        "shortName": "GLO",
        "id": "34dbbff8-88ce-11de-ad60-0019e336be3a"
      },
      "referenceFlow": {
        "name": "polybutadiene"
      },
      "metadata": {
        "similarity_score": 0.8650093078613281,
        "info": ""
      }
    }
  ]
}
```

Query	**I need to compare injection molding using ABS and HDPE**

Answer

```
{
  "similar_processes": {
    "injection_molding": [
      {
        "name": "injection moulding",
        "location": "RER",
        "similarity_score": 0.9269590377807617
```

```
      },
      {
        "name": "market for injection moulding",
        "location": "GLO",
        "similarity_score": 0.9269590377807617
      },
      {
        "name": "injection moulding",
        "location": "CA-QC",
        "similarity_score": 0.9264812469482422
      },
      {
        "name": "injection moulding",
        "location": "RoW",
        "similarity_score": 0.9262089729309082
      },
      {
        "name": "market for blow moulding",
        "location": "GLO",
        "similarity_score": 0.8663945198059082
      }
    ],
    "ABS": [
      {
        "name": "market for acrylonitrile-butadiene-styrene copolymer",
        "location": "GLO",
        "similarity_score": 0.8900270462036133
      },
      {
        "name": "acrylonitrile-butadiene-styrene copolymer production",
        "location": "RER",
        "similarity_score": 0.8900270462036133
      },
      {
        "name": "acrylonitrile-butadiene-styrene copolymer production",
        "location": "RoW",
        "similarity_score": 0.8900270462036133
      },
      {
        "name": "styrene-acrylonitrile copolymer production",
        "location": "RER",
        "similarity_score": 0.8736348152160645
      },
      {
        "name": "market for styrene-acrylonitrile copolymer",
        "location": "GLO",
        "similarity_score": 0.8736348152160645
      }
    ],
    "HDPE": [
      {
        "name": "polyethylene production, high density, granulate",
        "location": "RER",
        "similarity_score": 0.904289722442627
      },
      {
        "name": "market for polyethylene, high density, granulate",
        "location": "GLO",
        "similarity_score": 0.9037003517150879
      },
      {
```

```
        "name": "polyethylene production, low density, granulate",
        "location": "RER",
        "similarity_score": 0.881035327911377
      },
      {
        "name": "market for polyethylene, low density, granulate",
        "location": "GLO",
        "similarity_score": 0.8803625106811523
      },
      {
        "name": "polyethylene production, high density, granulate,
recycled",
        "location": "US",
        "similarity_score": 0.8788747787475586
      }
    ]
  }
}
```

Name of the partner The representative of QAT Responsible for business issues **Status:** Approved / Not Approved **Name:** ……………………………………………………………… **Date:** ………………………………………………	**Name of the partner** The representative of QAT Responsible for business issues **Status:** Approved / Not Approved **Name:** ……………………………………………………………… **Date:** ………………………………………………