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Circular and Dynamic Manufacturing Supply Chain Orchestration and Optimisation

D5.2 Final version of 3 Pilot Demonstrators

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Abbreviations

Acronym	Description
AI	Artificial Intelligence
AS IS	Current state
TO BE	Future state
BPMN	Business Process Model and Notation
CE	Circular Economy
interior CLT	Cross-laminated timber for interior usage
CM	Circular Manufacturing
CtG	Cradle to gate
EBSI	European Blockchain Services Infrastructure
ERP	Enterprise Resource Planning
EU	European Union
EXDs	Experiments for Demonstration
IoT	Internet of Things
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCC	Life Cycle Cost
MSMEs	Manufacturing Small & Medium Enterprises
PP	Polypropylene
rPP	Recycled polypropylene
SCDT	Supply Chain Digital Twin
SCOPT	Supply Chain Optimization
TRL	Technology Readiness Levels
WWT	Waste Water Treatment
GWP	Global Warming Potential

Executive Summary

This deliverable reports the final implementation and validation of the three pilot demonstrators developed within CIRCULOOS, addressing circular manufacturing applications in the wood, plastic, and leather sectors. The document describes the definition of AS-IS and TO-BE scenarios, the collection of Life Cycle Inventory (LCI) data, the modelling of processes and supply chains, and the comparative environmental and operational assessment of each pilot through Life Cycle Assessment (LCA) and Key Performance Indicators (KPIs).

Across all demonstrators, the adoption of circular strategies, including reclaimed wood sourcing, recycled plastic integration, and reuse of leather leftovers, resulted in measurable sustainability improvements. The analyses show reductions of up to ~50% in Global Warming Potential in the wood pilot and average impact reductions of 25–30% in the plastic pilot, alongside improved material efficiency and waste reduction in the leather pilot. These results confirm that targeted circular interventions can generate significant environmental benefits while maintaining technical feasibility and product quality.

Beyond the quantitative outcomes, the pilots validate the value of the integrated digital ecosystem developed in CIRCULOOS. Rather than relying on standalone assessment, sustainability evaluation is embedded within a broader decision-support workflow combining the Data Platform for information exchange, the Supply Chain Digital Twin for process modelling, optimisation tools for scenario exploration, and GRETA for environmental impact quantification. This toolchain enables companies to simulate and compare alternative supply chain configurations before implementation, supporting evidence-based and low-risk decision-making.

Overall, the deliverable demonstrates that digitally enabled orchestration and sustainability intelligence can effectively support MSMEs in redesigning their supply chains towards more circular, resource-efficient, and resilient models. The validated approach is scalable and replicable, providing a practical foundation for future Open Call experiments and for broader adoption of circular manufacturing practices across European industry.

1 Introduction

1.1 Project Introduction

The overarching vision of the present research project, CIRCULOOS, is to empower MSMEs to become integral members of Circular Manufacturing (CM) value chains. The project delivers a suite of tools designed to optimize and orchestrate end-to-end supply chains, integrating planning, execution monitoring, and transparent, real-time communication. By combining these capabilities with direct calculations of product sustainability and circularity profiles—accessible to both internal and external partners— CIRCULOOS enables the configuration and execution of innovative circular manufacturing processes. These processes promote sustainable production throughout the entire product life cycle, from recovering the value of end-of-life products to utilizing recycled and remanufactured materials.

To achieve this vision, CIRCULOOS deploys in its pilots the following key components:

- **Circular Supply Chain Orchestration**: an end-to-end system for collaborative workflows that incorporates planning and execution metrics, along with advanced, multimodal visualization and analytics.
- **Supply Chain Digital Twin (SCDT):** simulates and visualizes supply chain arrangements and factory workflows to provide a visual representation of the factory inputs, outputs, and internal processes as well as the interaction between the factories in the supply chain.
- **Supply Chain Optimization (SCOPT):** continuous monitoring of global (across the supply chain) and local (within the factory) processes, inputs, outputs, and configuration parameters. This enables data-driven decision-making, supporting ongoing optimization of performance and sustainability metrics.
- **Dynamic Sustainability Assessment (GRETA)**: a tool to explore alternative supply-chain scenarios—varying in materials, technologies, suppliers, and CE practices—and rapidly assess their sustainability impact.
- **CM-Specific Tools:** advanced machine vision and robotics for automatic recognition of recyclable parts, optimizing selection flows in the recycling process.
- **RAMP Data Platform:** leveraging the RAMP IoT platform, CIRCULOOS delivers a robust CM ecosystem, enabling MSMEs to adopt and scale circular practices.

1.2 Deliverable Purpose

The purpose of this deliverable is to provide insights within the WP5 – Execution of Demonstrators, which focuses on the practical implementation of circular manufacturing principles through real-world pilots and experiments. WP5 aims to leverage the circularity enablers (WP3) and the integrated platform (WP4) to facilitate the successful execution of the pilots and selected experiments, known as EXDs. A key objective of this WP is to scale the results from the EXDs to higher Technology Readiness Levels (TRL), enabling the developed solutions to be ready for market deployment. By integrating feedback from the pilots and EXDs, the deliverable also supports the results of the GRETA tool provided to the CIRCULOOS platform, showing its ability to drive circularity and sustainability across supply chains.

This work focuses on the **Pilots Execution Task (T5.1)**. This task entails implementing the supply chain demonstrators in real-world environments, following the architecture and utilizing the integrated platform from WP4, the enablers from WP3, and the pilot scenarios defined in WP2. The final goal is to create an integrated digital space where real-world entities, computational systems, tools, processes, and people can coexist and interact within a digital framework. This approach marks a departure from traditional hierarchical automation models, shifting towards a more collaborative and interconnected view of the supply chain, considering it as a unified team rather than focusing on individual factory needs. The demonstration takes place within the participating factories, allowing for the validation of novel circular manufacturing business models. Through this process, advanced tools are employed to assist the transition towards more circular and sustainable practices (Pachon et al., 2024). The outcomes were transformed into success stories that highlight the potential and impact of the demonstrators, while also serving to support further scaling within the selected open calls.

Specifically, this deliverable (D5.2 – Final Version of 3 Pilot Demonstrators), which consists of an update of the previous D5.1, aims to document the implementation of the three project pilots conducted in Spain, the Netherlands, and Hungary across the plastic, wood, and leather sectors. It presents the AS-IS and TO-BE scenarios for each pilot, the methodology used for assessing their sustainability performance, the tools employed (such as the CIRCULOOS platform and GRETA) to support data-driven analysis, and the results of the comparative assessment.

Moreover, the SCDT and SCOPT tools have been implemented. A data collection template has been developed by Cyprus University of Technology (CUT) to collect the necessary data for the SCDT and SCOPT tools from the partners of the three pilots. The template was developed to describe a wide range of processes and factory setups with general guidelines on how to complete the template. A series of one-to-one meetings between the CUT team and the pilot partners has been organised in order to present the SCDT template and explain how the template works using examples on how to fill it in. Based on the discussions with the pilot partners, the feedback provided on the template has been improved and refined to collect the necessary information. The information collected captures the complexity and variation of the pilot setups. Using the information, the SCDT tool was then fine-tuned and further developed to expand its capabilities and cover the needs of more complex setups. A recorded video detailing the description and the use of the template for data collection was developed and distributed among CIRCULOOS partners. One SCDT template has been completed by each partner of the pilots. The input materials, output products, the intra-factory processes and the suppliers are defined in the SCDT template.

The SCDT template consists of three parts:

1. General guidelines and information regarding the template and data required to be defined.
2. The flow diagram of the intra-factory logistics of the factory and the suppliers of the input materials/products.
3. The detailed description of the entities presented in the flow diagram. The input materials and products, their quantity and units should be defined. Also, the materials utilised as input by each process and the output products produced by each process should be defined.

Based on the data defined in the SCDT template, SCDT simulates the factory processes, the input materials used by each process, the quantity of the materials utilised by each process, the time required for each process to operate and the output products produced. SCDT visualises the quantity of the materials and products existing in the factory at a given instant, while indicating the status of each process (running, stopped, out of order). SCDT interacts with the SCOPT in order to visualise alternative solutions to tackle intra-factory and supply chain optimisation problems.

Moreover, SCOPT can be utilised as a verification tool that predicts the future conditions of intra-factory logistics and supply chain arrangements, providing feasible solutions or verifying if at least a solution exists. The results provided by SCOPT can be visualised in SCDT. SCDT can also be used to visualise real-time measurements acquired in the factory and transmitted to the Circuloos Data Platform.

The SCDT tool has been implemented to simulate the intra-factory logistics and the supply chain arrangement of the TO-BE scenarios of the 3 pilots, as presented in the deliverable D3.4 3D Digital Twin of supply chain/production/products M24. Furthermore, the SCOPT tool has been implemented to investigate and analyse supply chain and intra-factory orchestrations models motivated by the TO-BE scenarios of the 3 pilots, as presented in deliverable D3.8 AI and Data-driven Supply Chain Optimisation M24.

1.3 Overview of the Deliverable

This document provides a comprehensive overview of the current (AS-IS) and future (TO-BE) process scenarios under study, details the implementation of both models in GRETA for the three pilots, and presents the main outcomes generated in GRETA, which will be transferred to the CIRCULOOS platform in subsequent tasks. Similarly, it presents the results of the other tools in each pilot.

The Methodology section assesses the AS-IS and TO-BE scenarios for the wood, leather, and plastic pilots. Flow diagrams are developed to define the variables considered in the LCA analyses, followed by a detailed explanation of the data used to build the LCI. The section then describes the implementation of the pilot scenarios in GRETA and concludes with the presentation of results generated in GRETA, highlighting the sustainability impacts identified through the comparative LCA.

Overall, the current deliverable provides a thorough description of the pilot processes, with particular attention to defining the key variables that shape their performance and sustainability profile. It compiles and presents the data collected to construct the LCI, ensuring transparency and traceability of the information used in the analyses. Building on this foundation, the document carries out the comparative LCA calculations, presenting not only the methodology applied but also the results. In doing so, it offers a structured pathway from process characterization to impact evaluation, delivering insights that are essential for understanding the sustainability performance of the pilots and supporting informed decision-making.

2 Methodology

2.1 Description of AS-IS Scenarios

This section describes the three current business models of the pilots participating in the CIRCULOOS project. Its purpose is to present the existing business operations for each case, which served as the basis for identifying the weaknesses previously highlighted in Deliverable 2.1. The pilots are linked to the wood, plastic, and leather industries and are located in the Netherlands, Spain, and Hungary, respectively. Although these pilots were already introduced in earlier deliverables, particularly in Deliverable 5.2, this section provides the additional detail necessary to define the final version of the six models implemented in GRETA, covering both the current state (AS-IS) and the future state (TO-BE) for each of the three pilots.

Simplified flow diagrams are presented to identify the key variables that need to be connected with industrial processes in order to integrate them into GRETA, the LCA tool. By mapping out these processes, it is possible to pinpoint critical inputs, outputs, and interdependencies that influence environmental performance (Pachón et al., 2020). This structured approach ensures that all relevant data flows are properly captured and aligned with the requirements of the LCA methodology (Jordaan et al., 2021), allowing for a more accurate and comprehensive assessment of the sustainability impacts of the pilot projects.

The AS-IS and TO-BE flow diagrams for each pilot are based on the system boundaries defined in previous deliverables, which encompass all stages required to produce the material and energy inputs for the pilot process. They also include the emissions released during the process and the handling of both liquid and solid waste, including treatment through local wastewater facilities or incineration of solid waste nearby.

To evaluate the comparative LCA between the AS-IS and TO-BE scenarios, it is necessary to establish a clear definition of the products considered in each case. The following sections describe the products associated with both scenarios, as well as all components encompassed within the cradle-to-gate (CtG) system boundary of the study.

2.1.1 Wood Pilot AS-IS

Three independent wood-related companies have joined forces within the CIRCULOOS framework to participate in the Wood Pilot. The three companies operate in the Netherlands and specialize in different aspects of the wood supply chain independently.

Circu-leren is a company specializing in modular wood projects, including wooden houses, using primarily virgin wood. The company produces modular building materials designed for easy assembly and disassembly, ensuring an extended lifecycle for the final products. This approach allows furniture or houses to be dismantled and repurposed when they are no longer needed, enabling materials to be reused in new constructions and thereby minimizing waste. Although Circu-leren demonstrates a strong commitment to sustainability and circularity, it continues to rely heavily on virgin materials. This is largely due to the challenges associated with using recycled wood, including limited availability of suppliers, slower processing times, and difficulties in placing orders. A key area where the company relies mainly on virgin wood is the production of cross-laminated timber (CLT), a widely used material for wood-based modular housing. Their main objective is to enhance the circularity of their supply chain by collaborating with other companies that use locally sourced urban wood to produce comparable CLTs. They expect this approach will allow them to offer construction materials that match the performance of their current virgin-based products while integrating more sustainable and circular sourcing practices into future projects.

HERSO is another company that specializes in collecting and processing waste wood, recycling it into new, high-quality materials for various purposes. They are experts in crafting new furniture from reclaimed wood, giving discarded materials a second life. The company is largely human-driven, meaning that every time HERSO collects waste wood, the owner's expertise plays a crucial role in optimizing the process. The owner makes all the decisions regarding the design of specific furniture. They do not produce waste, as any leftover material from the fabrication of a specific piece is stored and can be used in future designs.

Finally, **Plennid** focuses on repurposing wood from urban trees that have been removed due to disease, storm damage, or city maintenance in Rotterdam. Rather than allowing this wood to be incinerated in low-efficiency electricity generation plants, they process and distribute it to third parties interested in high-quality reclaimed urban wood, thereby promoting a more sustainable approach to raw material sourcing.

Figure 1 shows the representation of the AS-IS scenario through the BPMN notation concerning the wood pilot, highlighting the main processes and data flows.

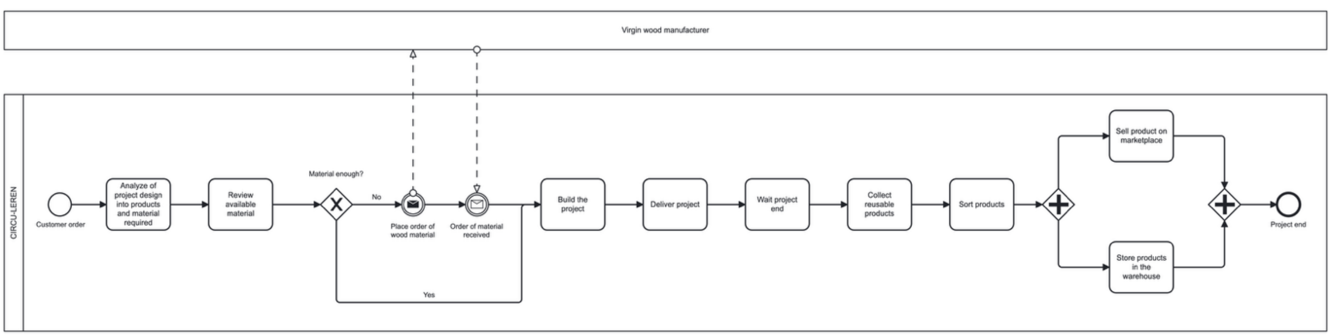

Figure 1 BPMN model for the Wood Pilot - AS-IS

LCA scenario modelling

In order to model the related scenario for making an LCA study, a simplified version of the process was made to identify the reference product(s), system boundaries and inputs and outputs for each process. Figure 2 illustrates the AS-IS scenario, where the reference products are the following:

- **CLT wood panel**, starting from virgin wood harvested from forests. The dimensions of that panel are 3.00 m × 1.25 m × 0.021 m, with a density of 460 kg/m^3, resulting in a weight of 38.5 kg. This panel is processed by different operations and then packaged.
- **electricity**, generated from damaged ornamental trees collected in the City of Rotterdam. The electricity produced is 43.84 kWh, derived from burning 54.8 kg of wood (the amount needed to produce the same CLT wood panel with virgin wood), with 20% efficiency at a cogeneration site and a calorific power coefficient of 4 kWh per kg of wood.

This current scenario, therefore, includes two products (multi-product system) derived from different raw materials. Electricity is included to ensure a fair comparison between the TO-BE scenario, where wood panels are produced from damaged ornamental trees, and the AS-IS scenario, where these trees are used for power generation. Transportations are taken into account in the following manner:

- **CLT wood panel:**
  - Berlin to Beverwijk – 690 km: CLT material
  - Beverwijk to Amsterdam – 25 km: CLT panel processed
  - Gorinchen to Amsterdam – 95 km: packaging material
  - Amsterdam to BLOK company – 25 kg: packaging material

- **Electricty:**
  - Forestry to co-generation site – 120 km: damaged ornamental wood

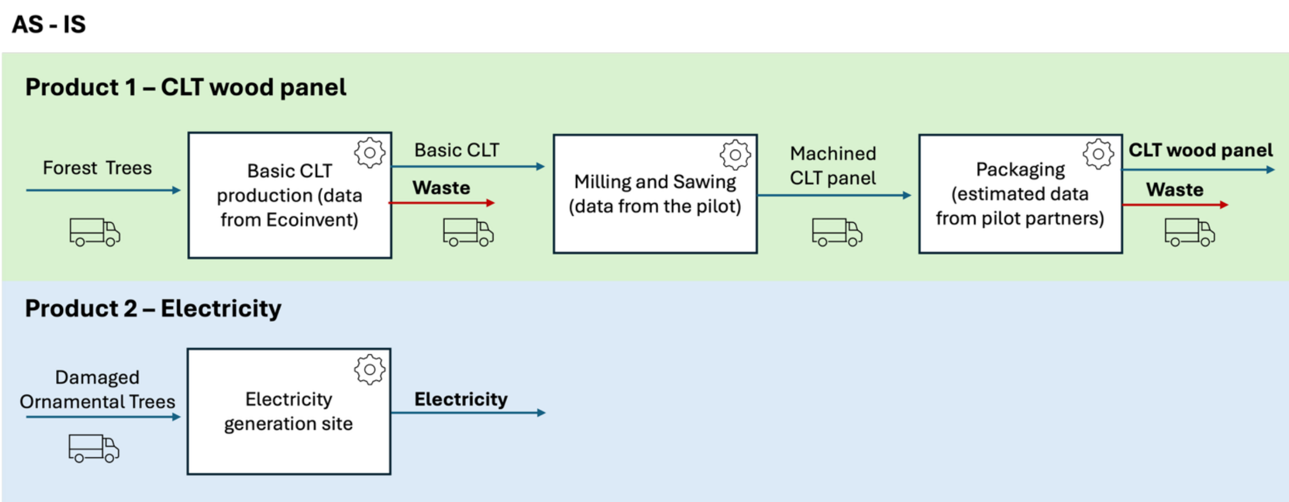

Figure 2 Wood Pilot LCA Model — AS IS Flow Diagram

2.1.2 Plastic Pilot AS-IS

Two independent companies specializing in plastics and one company focused on robotics for component identification in materials are participating in the so-called Plastic Pilot.

Thermolympic, based in Zaragoza, Spain, specializes in manufacturing plastic parts for the automotive and home appliance industries using various molding technologies. They rely on virgin raw materials for their products. In an effort to improve the sustainability of their business, they evaluated the possibility of incorporating recycled plastic into their feedstock. However, the company faced challenges in integrating recycled materials into the automotive industry due to customer requirements for high-quality, functional, and aesthetically precise parts. So far, they have not been able to implement recycled materials in their supply chain. Nevertheless, they are aware that some other clients, such as those in the home appliance industry, might be willing to accept recycled plastic if it meets specific characteristics. Currently, Thermolympic does not recycle its plastic waste, choosing incineration instead. This approach makes their processes less efficient, releases pollutants, and contributes to environmental impact.

Contenedores Lolo, the second company located in Spain, focuses on collecting and processing waste plastics. They purchase and collect plastics from wholesalers and retailers, aiming to provide high-quality recycled materials for various applications.

Canonical Robots acts as a third-party contributor to this pilot. While their involvement in the initial phase of the project is not planned, they are expected to play a significant role in the upcoming phases, particularly through open calls. They offer technological solutions to improve recycling processes. Specializing in robotics and automation, they focus on the identification and classification of recycled plastics. Their technology optimizes the recycling process by automating the sorting and qualification of plastics to ensure they meet the required standards for reuse in manufacturing new products. Currently, they collaborate closely with Contenedores Lolo to assist in qualifying the recycled and processed plastics.

Figure 3 shows the representation of the AS-IS scenario through the BPMN notation concerning the plastic pilot, highlighting the main processes and data flows.

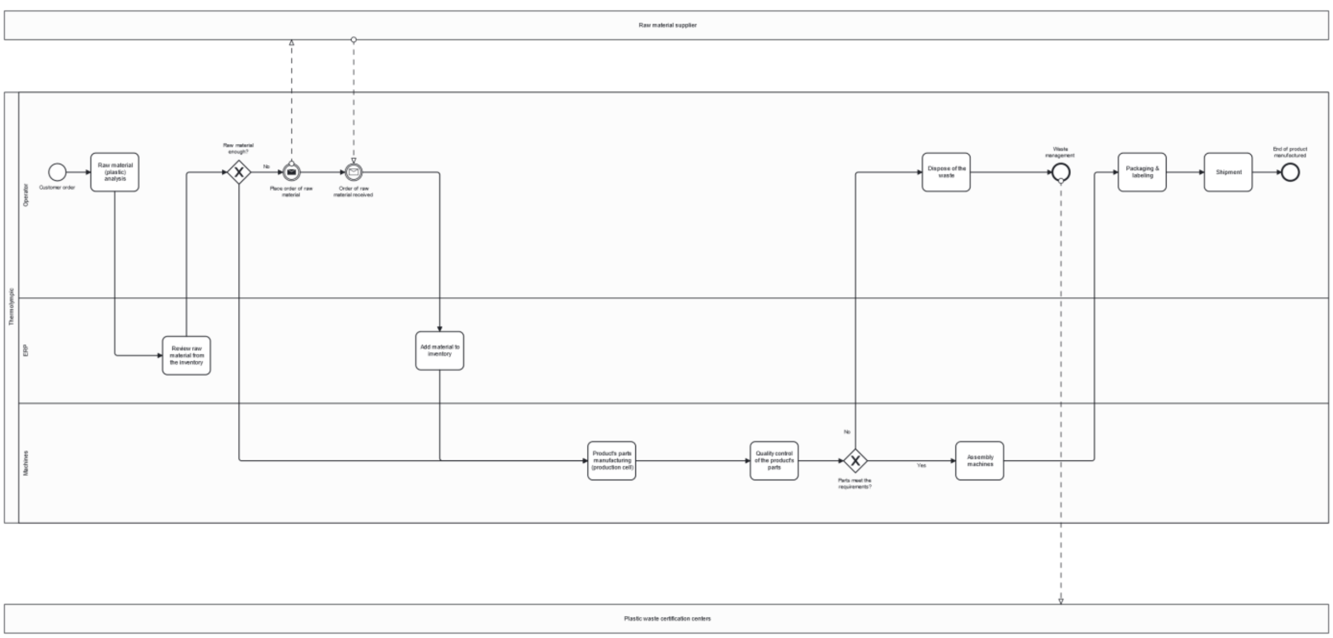

Figure 3 BPMN model for the Plastic Pilot - AS-IS

LCA scenario modelling

In order to model the related scenario for making an LCA study, a simplified version of the process was made to identify the reference product(s), system boundaries and inputs and outputs for each process. Figure 4 illustrates the AS-IS scenario, where the reference product is the following:

- **Washing machine detergent dispenser**, of a weight of 0,81kg, produced by combining five diverse plastic components (a lid, a distributor, a fixed tub, a sliding tub, and a siphon) made by three different plastics (ISOFIL H50 C2V NATURALSIRMAX, Hostacom HKC 182 L W92607 WHITE, ISOFIL HK 30 TFH2 BL2092 (blue)) and other ancillary metal materials (clamp and pipes). The scrap generated during the injection moulding process for the three different plastics (five different products) is incinerated in this AS-IS scenario.

This case is a single product system, where the only product is the washing machine detergent dispenser. Transportation is taken into account for all three raw plastic materials and the delivery of the product to the customer, as well as the processes of production of the three different plastics.

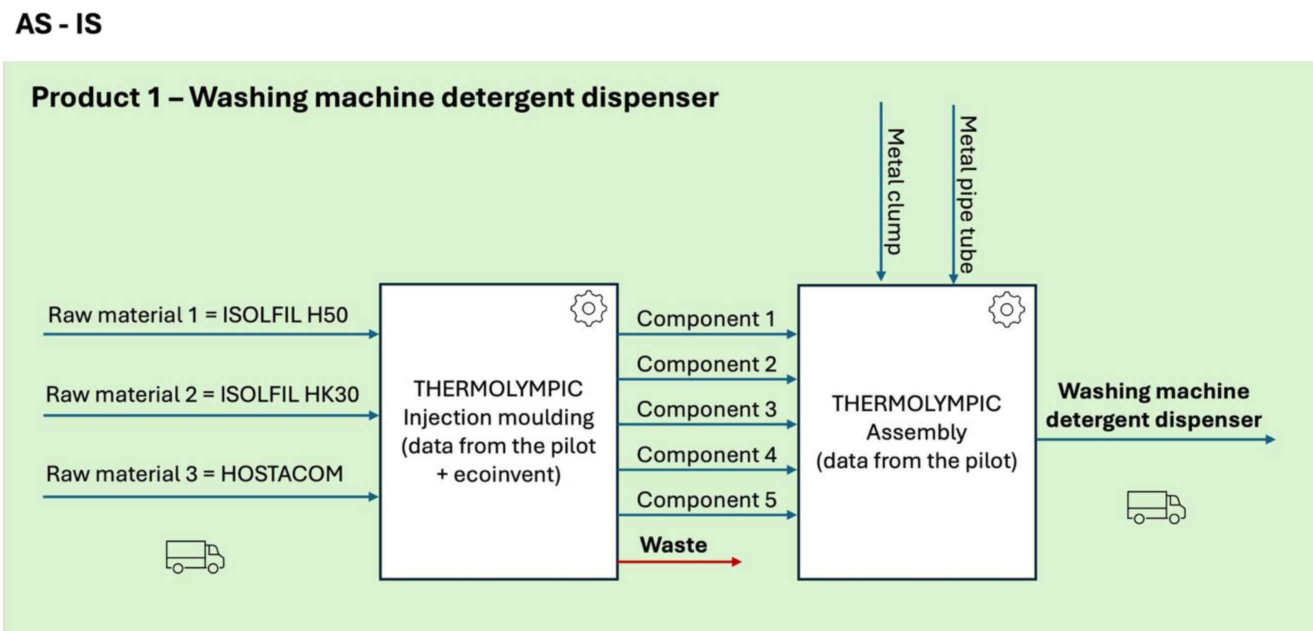

Figure 4 **Plastic Pilot LCA Model — AS IS Flow Diagram**

2.1.3 Leather Pilot AS-IS

Two independent companies in the leather goods industry, based in Hungary, have joined the CIRCULOOS project to establish the Leather Pilot. The companies, Mototextil Kft. (which replaces the previous partner KHOANI with the same role in the pilot) and B&A Kft., each specialised in different aspects of leather goods production and has operated independently up to this point.

Mototextil specialises in manufacturing leather and textile products. The company uses a wide range of fabrics, including automotive upholstery, artificial leather, and genuine leather. They also use various upholstery accessories and materials in their production processes, emphasising high-quality raw materials and customer service. At the beginning of the project, they only relied on virgin raw material and landfilled leftovers.

B&A focuses on producing small leather goods and generates waste during its manufacturing processes. The company, like the previous one, relies exclusively on virgin raw materials and wastes leftovers, leading to significant environmental impact.

Figure 5 shows the representation of the AS-IS scenario through the BPMN notation concerning the wood pilot, highlighting the main processes and data flows.

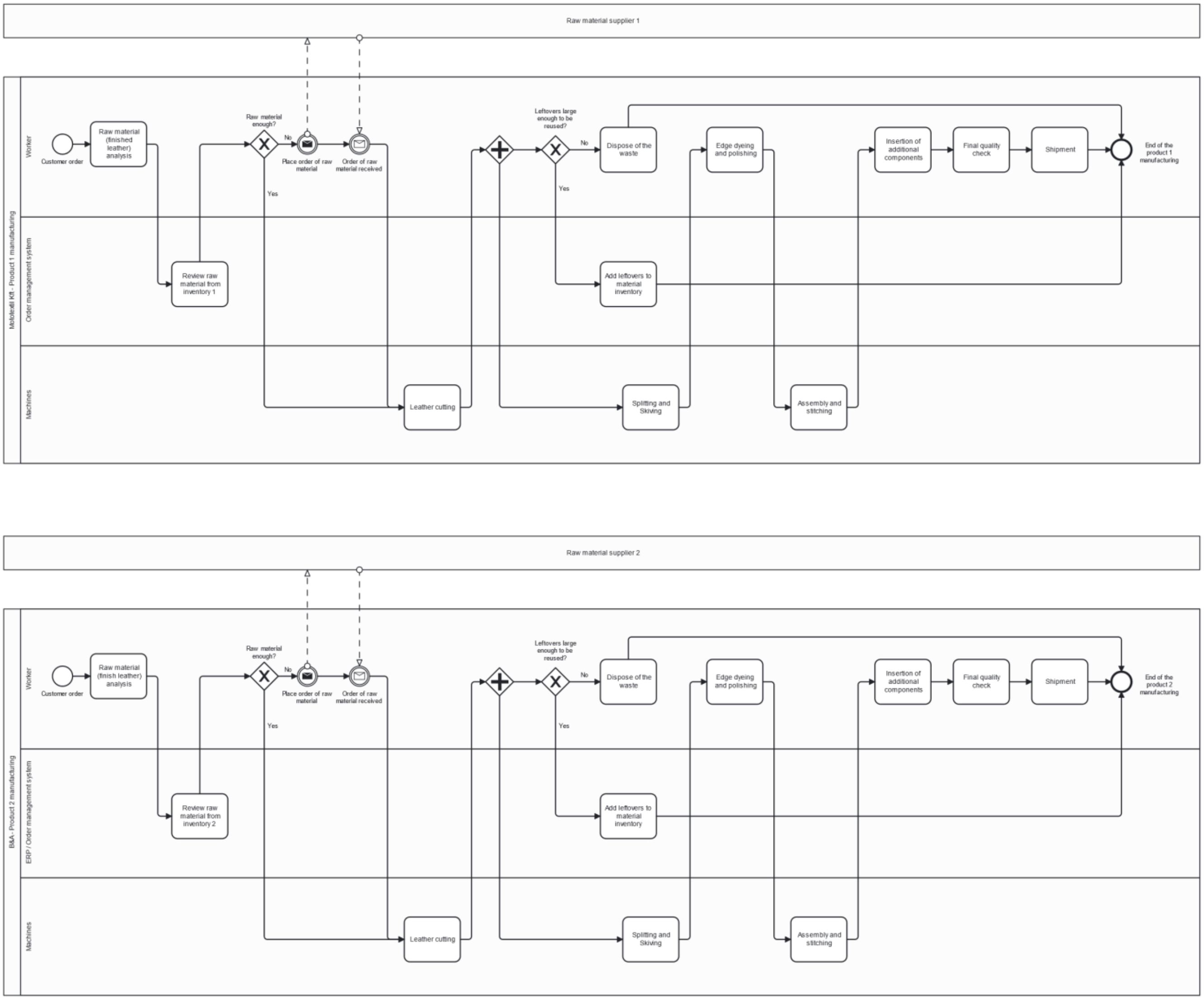

Figure 5 BPMN model for the Leather Pilot - AS-IS

LCA scenario modelling

In order to model the related scenario for making an LCA study, a simplified version of the process was made to identify the reference product(s), system boundaries and inputs and outputs for each process. Figure 6 illustrates the AS-IS scenario, where the reference product is the following:

- **leather bag**, of a weight of 2 kg, produced from virgin finished leather (after the tanning process)
- **leather keyholder** of a weight of 0,6 kg, produced from virgin finished leather (after the tanning process)

The flow diagrams and associated LCA models for the bag and keyholder are essentially identical, as the products are very similar. The main difference lies in the quantity of parameters involved, such as kilograms of raw materials and energy, etc.

In this case, allocation is required in order to distribute the environmental impacts associated with leather production from the animal among its different co-products (meat and raw hide in this scenario). Allocation is a method used in LCA when several outputs result from a single process, ensuring that the environmental burdens are fairly assigned to each product. The allocation factor for rawhide, obtained from the literature (De Rosa-Giglio et al., 2018), is 0,035. This means that 3.5% of the total impacts from livestock to slaughtering are allocated to leather, with the remaining impacts assigned to meat.

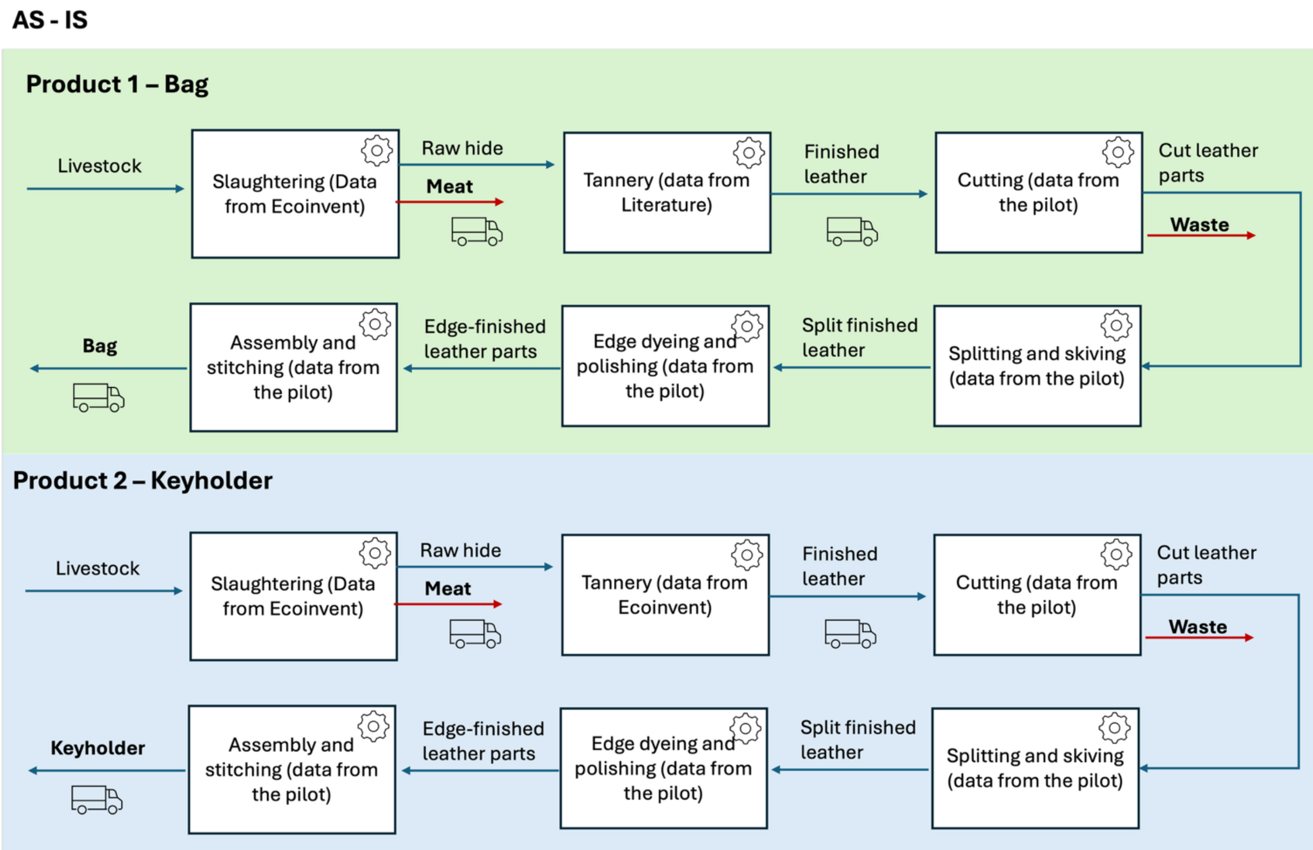

Figure 6 **Leather Pilot LCA Model — AS IS Flow Diagram**

2.2 Description of TO-BE Scenarios

This section outlines the proposed future business models for the three pilots of the CIRCULOOS project. The aim is to establish an enhanced operational framework that directly addresses the weaknesses identified in Deliverable 2.1, while fostering greater efficiency, sustainability, circularity, and resilience in each case. The scenarios presented build upon those previously defined in Deliverable 5.1.

2.2.1 Wood Pilot TO-BE

In an effort to develop a more sustainable, efficient, and resilient business model, the three independent wood-related companies have united under a consortium within the Wood Pilot. This pilot seeks to integrate their operations, fostering a circular economy approach that minimizes dependence on virgin wood raw materials, optimizes resource utilization, and enhances overall competitiveness and innovation within the industry.

By working together, these companies streamline production processes and create higher-value products from reclaimed materials. Circu Leren plans to use building blocks manufactured by HERSO using wood from Plennid's urban timber, offering a sustainable alternative to traditional cross-laminated timber (interior CLT) panels. The integration between Plennid, HERSO, and Circu Leren is designed to create a seamless and efficient supply chain that maximizes the value of urban wood. Plennid specializes in sourcing,collecting and sawing urban trees into urban wood, which is then processed by HERSO, an expert in recycling and refining wood materials. Once the wood is repurposed, Circu Leren buys the wooden building panels from Herso.

This collaborative workflow will be assessed using life cycle thinking to ensure the establishment of a closed-loop system, where materials are continuously reused, and the industry's carbon footprint is measured and compared against the benchmark—interior CLT panels—to evaluate its environmental benefits.

This initiative exemplifies how collaborative circular economy models can drive both environmental and economic benefits, particularly for SMEs in the wood industry. Beyond environmental impact, this partnership aims to boost profitability, strengthen market positioning, and serve as a scalable blueprint for broader industry transformation. If successful, the model could be expanded to include additional companies, fostering a more circular and regenerative wood sector while encouraging widespread adoption of sustainable business practices.

Figure 7 shows the representation of the TO-BE scenario through the BPMN notation concerning the wood pilot, highlighting the main processes and information flows. Process tasks colored yellow indicate activity on the RAMP.eu web interface, tasks colored blue indicate data exchange with the CIRCULOOS Data Platform and tasks colored green indicate 'shipping' tasks where the environmental impact is variable and depends every time on the specific supply chain that is formed.

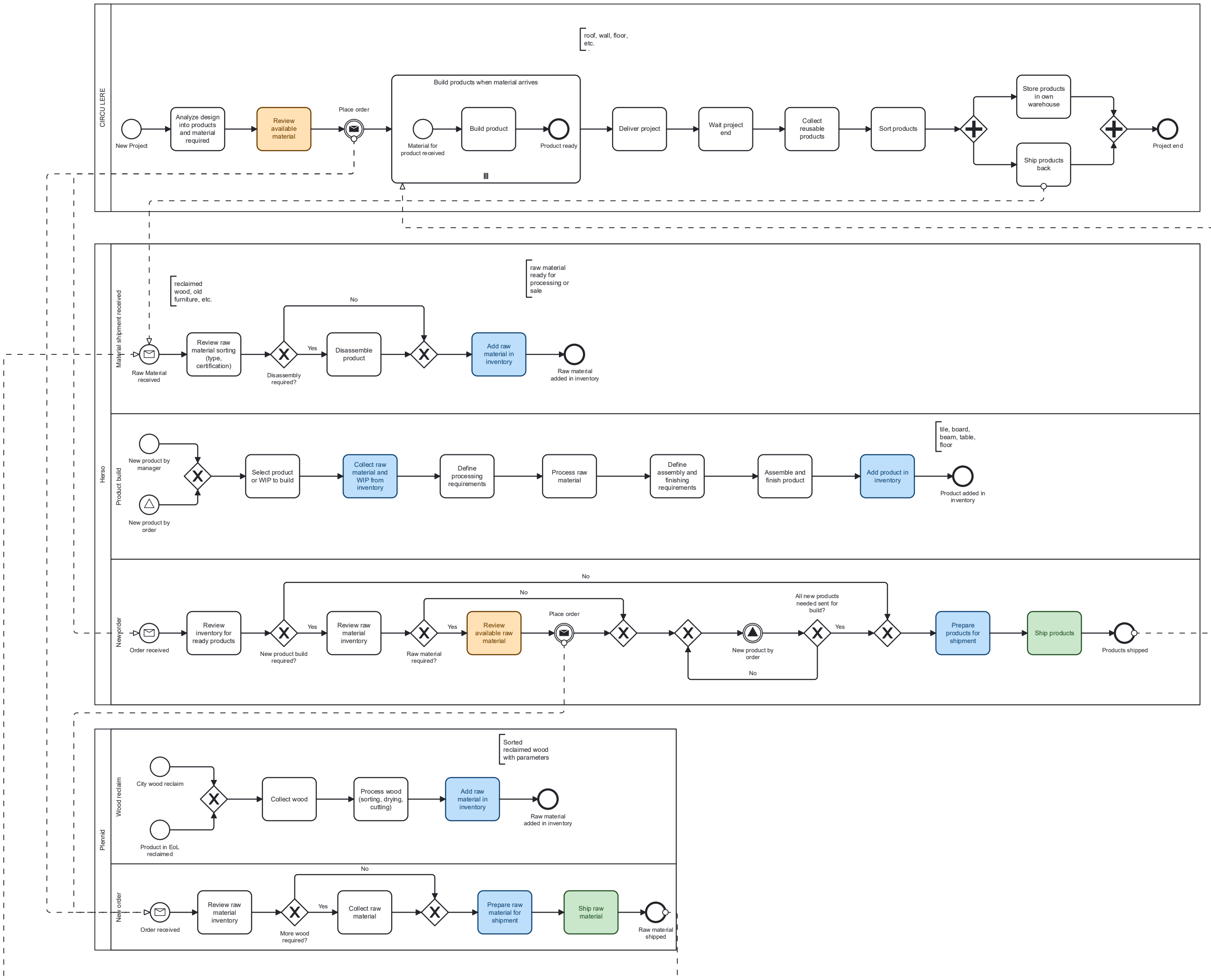

Figure 7 BPMN model for the Wood Pilot – TO-BE

Process Orchestrator and explanation of processes

Figure 7 illustrates the business-level process of the whole supply chain for the Wood Pilot. The Process Orchestrator manages the process of each actor (indicated as a 'swim lane' in the model), taking decisions were appropriate, gathering user input (either for indicate the fulfillment of a task, or to gather data) and communicating with external systems as needed. More detail on how the process is executed within the Process Orchestrator is given in deliverable D3.2. Each actor's internal processes are explained below, and are connected to the other actors as indicated in the model:

- CIRCULEREN: CIRCULEREN's main process starts when a new project is launched. CIRCULEREN analyses the requirements of the project and the material that is needed and proceeds to review the available material for sale on RAMP.eu. Once the provider is selected, an order is placed to buy the material (in the pilot case, this is Herso). Then the material is received by the provider and the products needed for the project are built. The project is delivered and when the project ends, CIRCULEREN recollects and sorts reusable products. These products are either stored in their own warehouse or are sent back to the provider, and the overall CIRCULEREN process is finished.

- HERSO: Herso has 3 main internal parallel processes: 1) Collecting and sorting raw material, and making it ready for producing products or selling it (hence, this process ends with adding the material to RAMP.eu), 2) Producing a product, that can be launched either by the manager or because of an order, which ends in adding the product to the inventory (either for sale or for a specific order), and 3) Executing an order, explained in more detail: When an order is received, inventory is checked for available products in the inventory. If available products are sufficient for the order, the order is prepared and shipped. If products need to be produced, the available raw material is checked. If available raw material is sufficient, the production of products is triggered, and once the products are ready, they are shipped. If raw material is not sufficient, available material for sale is checked on RAMP.eu and an order is placed to the selected provider (in the pilot case, this is Plennid). Once raw material is received, the production of the order products and shipping follows, as above.
- PLENNID: Plennid has 2 main internal parallel processes: 1) Collecting and sorting raw material, for city wood in EoI, processing it and making it available for sale, and 2) Executing and order, by preparing the available material for shipping, or collecting more if required.

LCA scenario modelling

In order to model the related scenario for making an LCA study, a simplified version of the process was made to identify the reference product(s), system boundaries and inputs and outputs for each process. Figure 8 illustrates the TO-BE scenario, where the reference products are the following:

- **Reclaimed wood panel**, starting from ornamental trees collected in the City of Rotterdam. The dimensions of that panel are 3.00 m × 1.25 m × 0.021 m, with a density of 700 kg/m^3, resulting in a weight of 54.8 kg. This panel is processed by different operations and then packaged.
- **electricity**, generated from the mix of resources used for making the Dutch energy mix. The electricity produced is 43.84 kWh, as is the case in the AS-IS scenario.

Transportations are taken into account in the following manner:

- **CLT wood panel:**
  - Rotterdam to PLENNID site – 20 km: CLT material
  - PLENNID site to HERSO site – 95 km: CLT panel processed
  - HERSO site to CIRCLUREN site – 90 km: packaging material

Furthermore, in this scenario, the effects of cutting trees for CLT panels are considered avoided impacts. The key benefit is that the forest remains undisturbed, preventing impacts related to harvesting new wood.

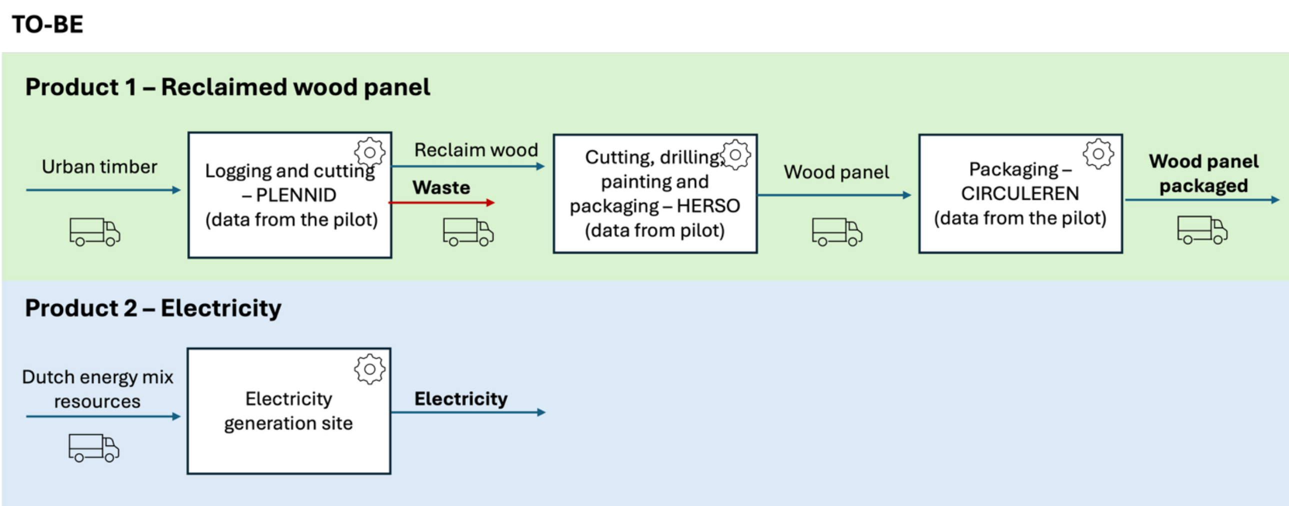

Figure 8 Wood Pilot LCA Model — TO BE Flow Diagram

CIRCULOOS Data Platform

CIRCULOOS Data Platform is utilised to gather and make available the relevant data (information and parameters) that need to be shared across the supply chain. Changes in the data that is stored are expected to take place in the blue-colored tasks, with the Process Orchestrator sending the relevant triggers and user input. More specifically, in the wood pilot, the CIRCULOOS Data Platform facilitates the sharing of the data related to the following kinds of material (also indicating the lifecycle of the material itself from reclaimed wood to the final wood product):

1. Wood (Urban) that can be used as raw material
2. Wood that can be used as production material for wood products, with relevant parameters and certification if applicable,
3. Wood products, specifying type and parameters (tile, board, beam, table, floor)

Supply Chain Digital Twin (SCDT)

The SCDT component has been implemented to model the intra-factory logistics of Circuleren, Herso and Plennid, as well as the interconnections between the three companies of the wood pilot along with the input received by the suppliers of the wood pilot. Based on the detailed description of the processes, input/output materials, scraps and suppliers included in SCDT template, three flow diagrams have been constructed, one for each partner of the wood pilot. As captured by the SCDT template, Figure 9 illustrates the workflow of Herso, Figure 10 illustrates the workflow of Plennid and Figure 11 illustrates the workflow of Circuleren. Detailed description of the SCDT can be found in the deliverable D3.4 3D Digital Twin of supply chain/production/products M24.

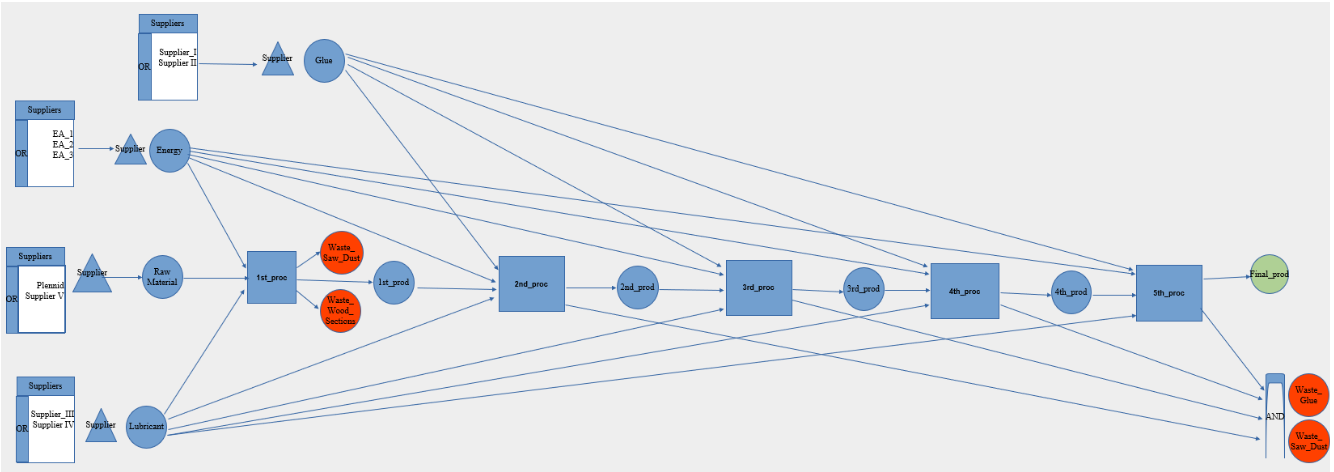

Figure 9: Workflow diagram of Herso in SCDT template.

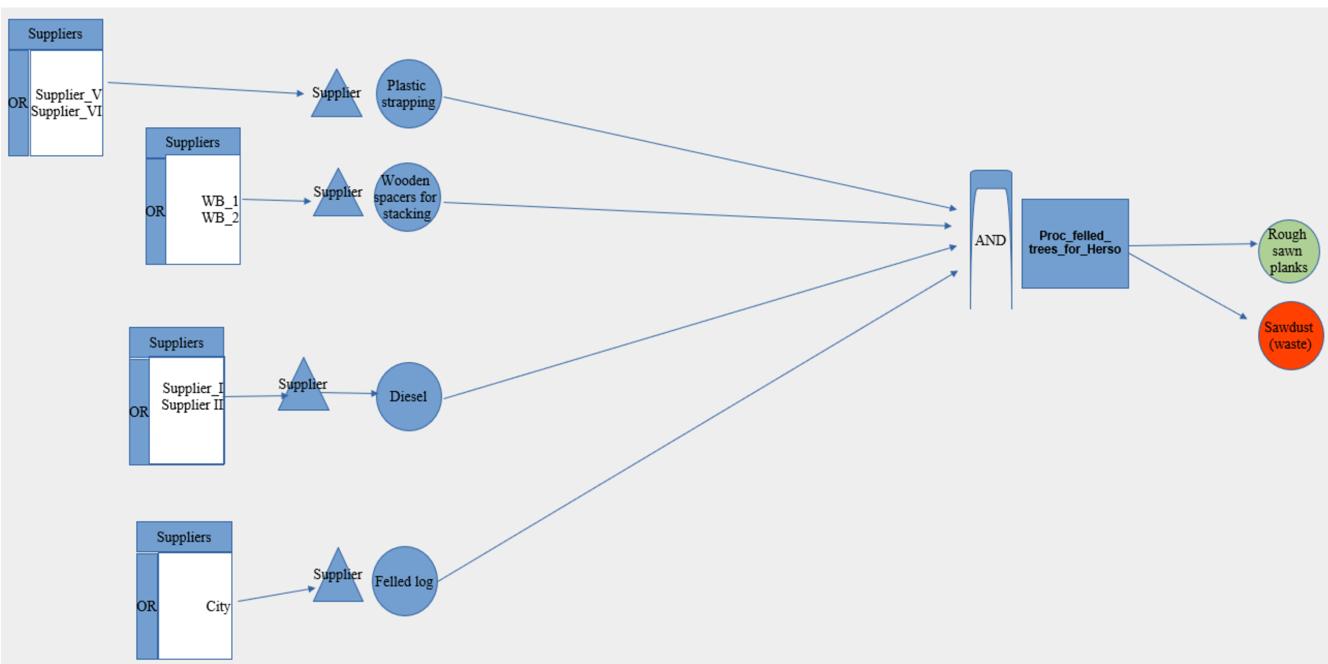

Figure 10: Workflow diagram of Plennid in SCDT template.

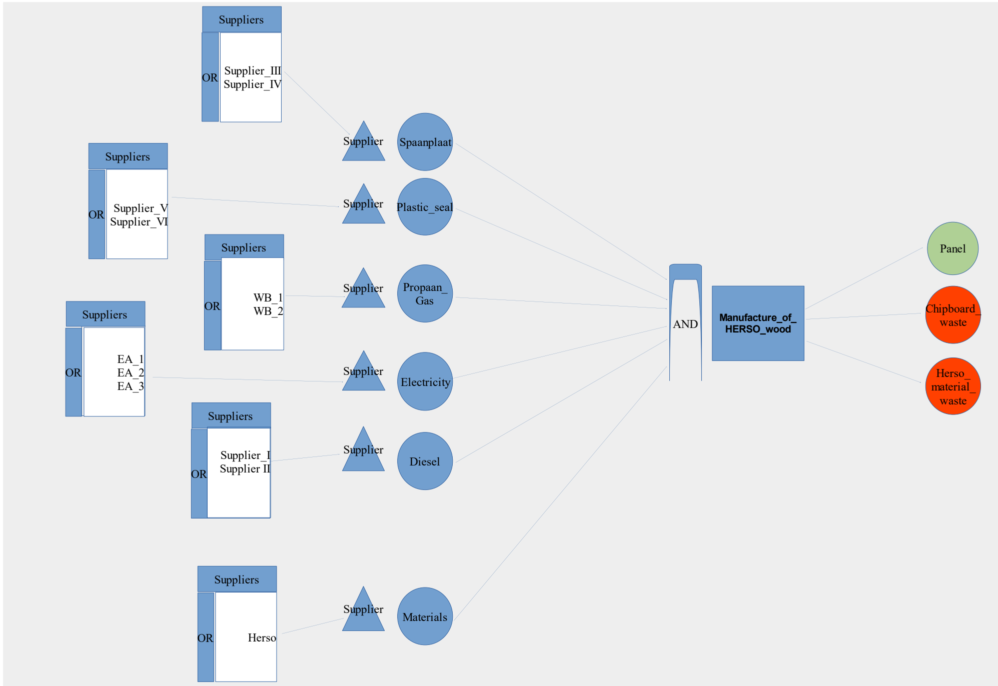

Figure 11: Workflow diagram of Circuleren in SCDT template.

Supply Chain Optimization (SCOPT)

The SCOPT component has been implemented in a supply chain scenario motivated by the CIRCULOOS wood pilot to investigate alternative and feasible supply chain arrangements, maintaining a core of three companies in a supply chain while exploring the benefits of possibly including additional companies in the supply chain in order to reduce the wood scrap. The objectives are to minimise the buffer level of the wood scrap produced and produce new products from recycled wood scrap or recycled wood materials, while keeping the current supply chain arrangement of the wood pilot as the core of the proposed solution. Detailed description of the SCOPT implementation can be found in the deliverable D3.8 AI and Data-driven Supply Chain Optimisation M24.

2.2.2 Plastic Pilot TO-BE

In an effort to establish a more sustainable and efficient business model, the two independent companies in the plastics sector (Thermolympic and Contenedores Lolo) have formed a synergie within the Plastic Pilot. This pilot project aims to integrate their operations, fostering a circular economy approach that maximizes resource utilization, minimizes waste, and enhances overall competitiveness in the industry.

Thermolympic plans to utilize recycled plastics processed by Contenedores Lolo, incorporating them into their manufacturing processes to produce a specific component that meets both recycled content and quality requirements. This component is a white plastic product used in the home appliance industry, specifically designed to hold detergent inside washing machines. The collaboration between these two entities will be assessed using Life Cycle methodologies to evaluate the benefits of their integration. The current product will be evaluated against the proposed new product to highlight potential improvements in reducing reliance on virgin plastic resources and environmental impact.

This partnership exemplifies a circular economy model within the plastics industry, demonstrating how small enterprises can collectively achieve significant sustainability objectives, enhance profitability, and strengthen market positions. If successful, this approach could be expanded to include additional companies, further promoting CE principles in the plastics sector.

Figure 12 shows the representation of the TO-BE scenario through the BPMN notation concerning the plastic pilot, highlighting the main processes and flows. Process tasks colored yellow indicate activity on the RAMP. In the EU web interface, tasks coloured blue indicate data exchange with the CIRCULOOS Data Platform, while tasks coloured green indicate 'shipping' tasks where the environmental impact varies depending on the specific supply chain formed.

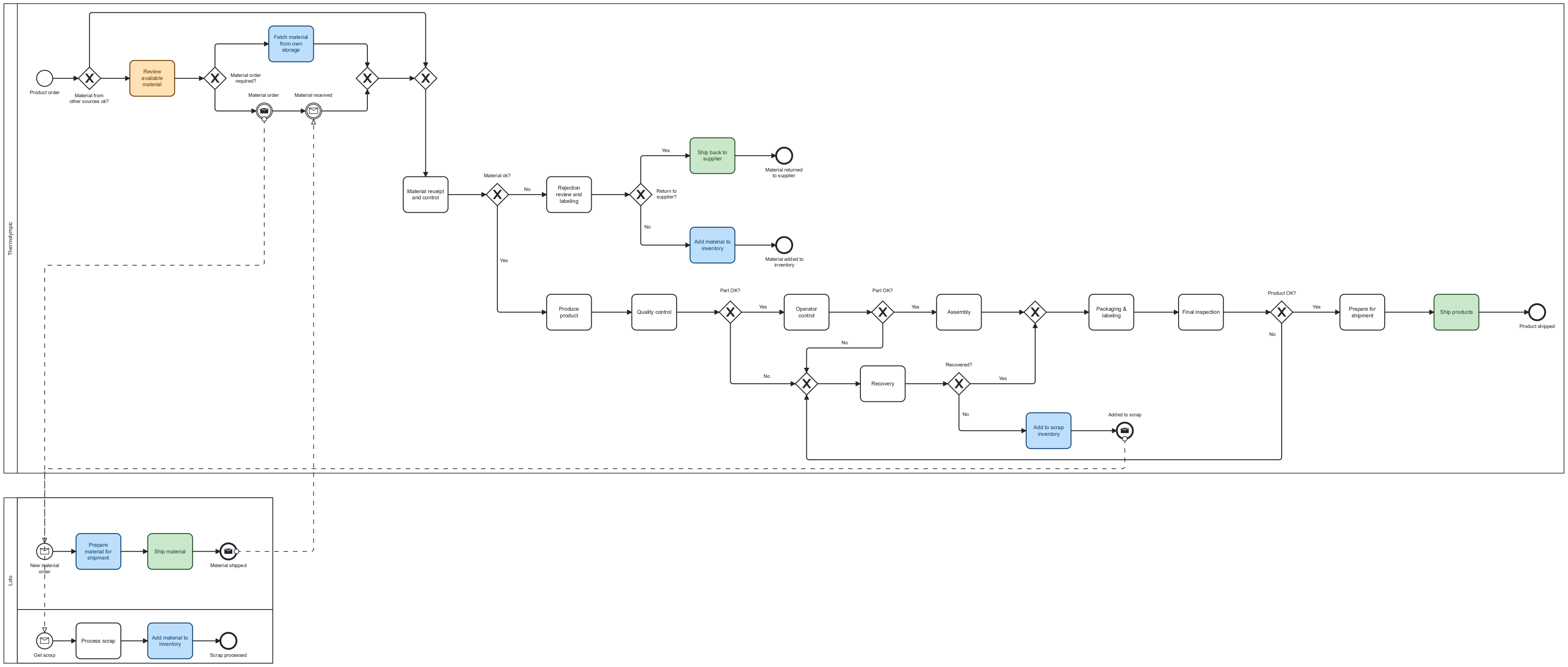

Figure 12 BPMN model for the Plastic Pilot – TO-BE

Process Orchestrator and explanation of processes

Each actor's processes are explained as follows:

1. THERMOLYMPIC: One main process is included, triggered by a new order. The first decision is, based on the order, whether virgin raw material is required or if material from other sources, like recycled plastic, can be used. When material from other sources may be used, the available material (own inventory and data on the Data Platform) is reviewed. If material in the own repository is sufficient, it is fetched and forwarded to the production line material reception; else an order is placed to the selected supplier. The raw material is checked (receipt and control), where the material is once again inspected. If material is rejected, it is labelled and according to its quality, it is either returned to the supplier or stored within its own inventory for another order. If it is accepted, it is forwarded for production. Along the production and up to packaging, there are quality controls. When a part (in progress or final) is considered

LCA scenario modelling

In order to model the related scenario for making an LCA study, a simplified version of the process was made to identify the reference product(s), system boundaries and inputs and outputs for each process. Figure 13 illustrates the TO-BE scenario, where the reference product is the following:

- **Washing machine detergent dispenser**, of a weight of 0,81kg, produced by combining five diverse plastic components (a lid, a distributor, a fixed tub, a sliding tub, and a siphon) made by three different plastics (with virgin and recycled granulates mixed in different percentages depending on the material considered) and other ancillary metal materials (clamp and pipes). The scrap generated during the injection moulding process for the three different plastics (five different products) is sent to the LOLO recycling centre in this TO-BE scenario.

Going into the experiment detail, the lid and distributor are made from ISOFIL H50 C2V NATURALSIRMAX, the fixed and sliding tubs are made from Hostacom HKC 182 L W92607 WHITE, and the siphon is made from ISOFIL HK 30 TFH2 BL2092 (blue), while the other parts are white plastic. The siphon is the only part that does not produce scrap in the plant, so its recycled material must come from external sources. The other parts (the white components) do generate scrap during production. This scrap is collected and recycled within Contenedores LOLO through the so-called "CONTENEDORES LOLO Recycling" process (see Figure 13), which reincorporates it into the supply chain. However, since the amount of scrap produced is insufficient to meet demand, additional recycled material from external sources is also used to reach the desired recycling ratio in the feedstock. The external sources may consist of companies that deposit their production scraps free of charge at Contenedores Lolo. In LCA terms, these scraps can be classified as waste, since the supplying companies receive no economic or material benefit from providing them. As such, the environmental impacts of these scraps are generally allocated as zero to the recipient process, in line with standard waste allocation principles.

Additionally, several tests in Thermolympic were conducted to determine the optimal ratio of recycled to virgin material for meeting quality standards and maximising the reuse of recycled plastic. The result is that 50% of recycled ISOFIL H50 C2V NATURALSIRMAX, 50% of recycled Hostacom HKC 182 L W92607 WHITE, and 0% of recycled ISOFIL HK 30 TFH2 BL2092 (blue)—since LOLO didn't provide that recycled material for the testing—can be used in the production process. The use of recycled plastic doesn't affect the energy required during the injection moulding process.

Finally, transportation is considered for all three virgin plastic materials, recycled material, and delivery of the product to the customer.

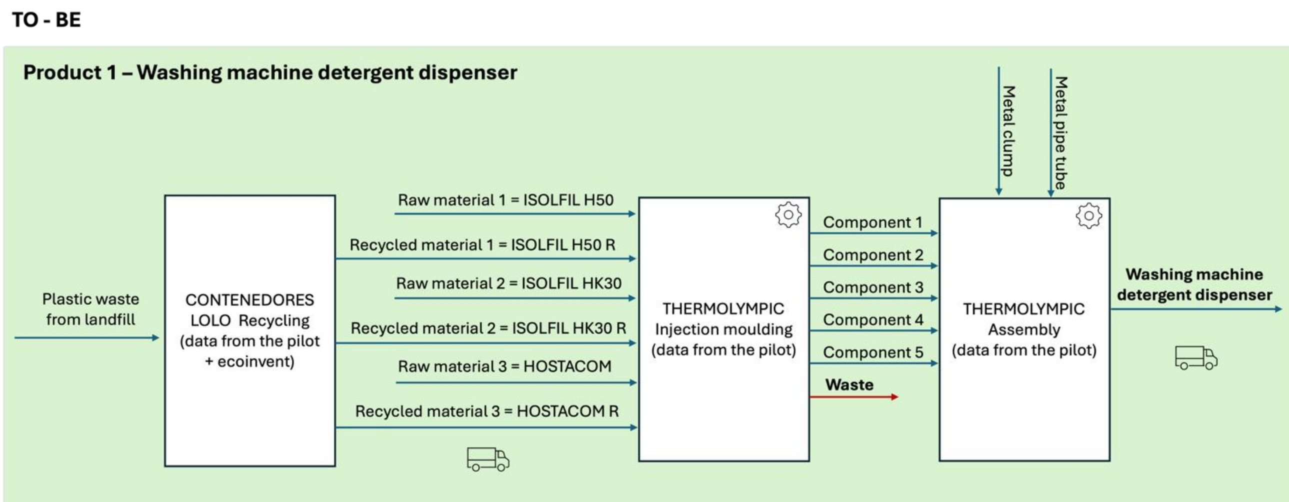

Figure 13 **Plastic Pilot LCA Model — TO BE Flow Diagram**

CIRCULOOS Data Platform

The CIRCULOOS Data Platform facilitates the sharing of the data related to the following kinds of material:

1. Processed (i.e., grinded) recycled material for reuse
2. Mixed (including recycled) raw plastic material (i.e., this is the raw material that is rejected in the reception of the specific order, but which can be reused in another order, e.g., with different requirements)
3. Scrap plastic products (i.e., those that have not passed the quality check)

Supply Chain Digital Twin (SCDT)

The SCDT has been implemented in the plastic pilot to model the intra-factory logistics of Thermolympic and LOLO, as well as the interconnections between the factories with the suppliers/consumers in the plastic pilot supply chain. Based on the detailed description of the processes, input/output materials, scraps and suppliers included in SCDT template, two flow diagrams have been constructed, one for each partner of the plastic pilot. As captured by the SCDT template, Figure 14 illustrates the workflow of Thermolympic and Figure 15 illustrates the workflow of LOLO. Detailed description of the SCDT can be found in the deliverable D3.4 3D Digital Twin of supply chain/production/products M24.

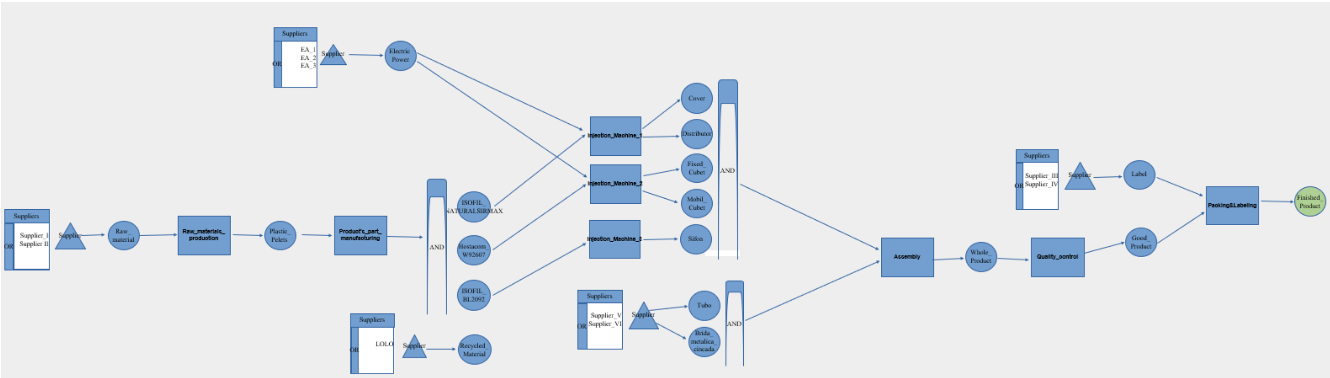

Figure 14: Workflow diagram of Thermolympic in SCDT template.

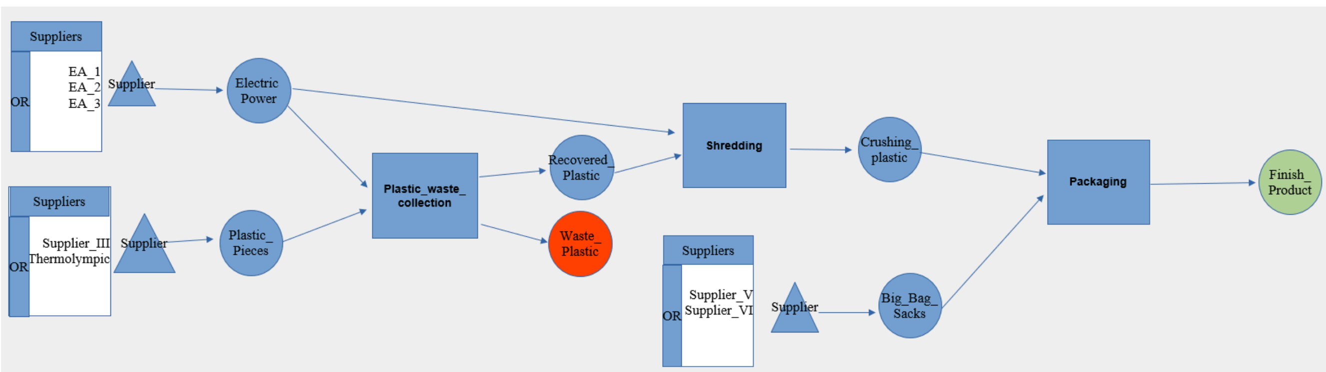

Figure 15: Workflow diagram of LOLO in SCDT template.

Supply Chain Optimization (SCOPT)

The SCOPT component is implemented in a supply chain motivated by the CIRCULOOS plastic pilot to investigate alternative supply chain arrangements, proposing alternative suppliers for the CIRCULOOS plastic pilot that provide plastic waste to the pilot in order to produce new products from recycled plastic waste, as well as to identify the interconnections between the actors in the supply chain proposed by SCOPT. Moreover, the supply chain scenario has been extended by incorporating an alternative supplier for the plastic pellet in order to present how the analysis provided by SCOPT is affected by incorporating a new supplier that provides additional units of plastic pellet in the supply chain to enhance the circularity of the CIRCULOOS plastic pilot. Detailed description of the SCOPT implementation can be found in the deliverable D3.8 AI and Data-driven Supply Chain Optimisation M24.

2.2.3 Leather Pilot TO-BE

In this pilot, two independent companies in the leather goods industry located in Hungary have formed the Leather Pilot to improve the sustainability of their leather goods products. This pilot aims to integrate their operations, fostering a CE approach that minimizes waste, and enhances overall competitiveness in the leather goods industry.

Through this collaboration, Mototextil will supply its leather leftovers to B&A for repurposing into new products, effectively reducing waste and minimizing the need for virgin materials. Any materials (leftovers) not utilized by B&A will be listed on a shared marketplace, allowing other interested parties to repurpose them, further promoting sustainability within the industry.

This partnership exemplifies a circular economy model within the leather goods industry, demonstrating how small enterprises can collectively achieve significant sustainability objectives, enhance profitability, and strengthen market positions. If successful, this approach could be expanded to include additional companies and other reusers (schools, kindergartens, etc.), further promoting CE principles in the leather goods sector and among consumers and broader society

Figure 17 shows the representation of the TO-BE scenario through the BPMN notation concerning the leather pilot, highlighting the main processes and information flows. Process tasks colored yellow indicate activity on the RAMP.eu web interface, tasks colored blue indicate data exchange with the CIRCULOOS Data Platform and tasks colored green indicate 'shipping' tasks where the environmental impact is variable and depends every time on the specific supply chain that is formed.

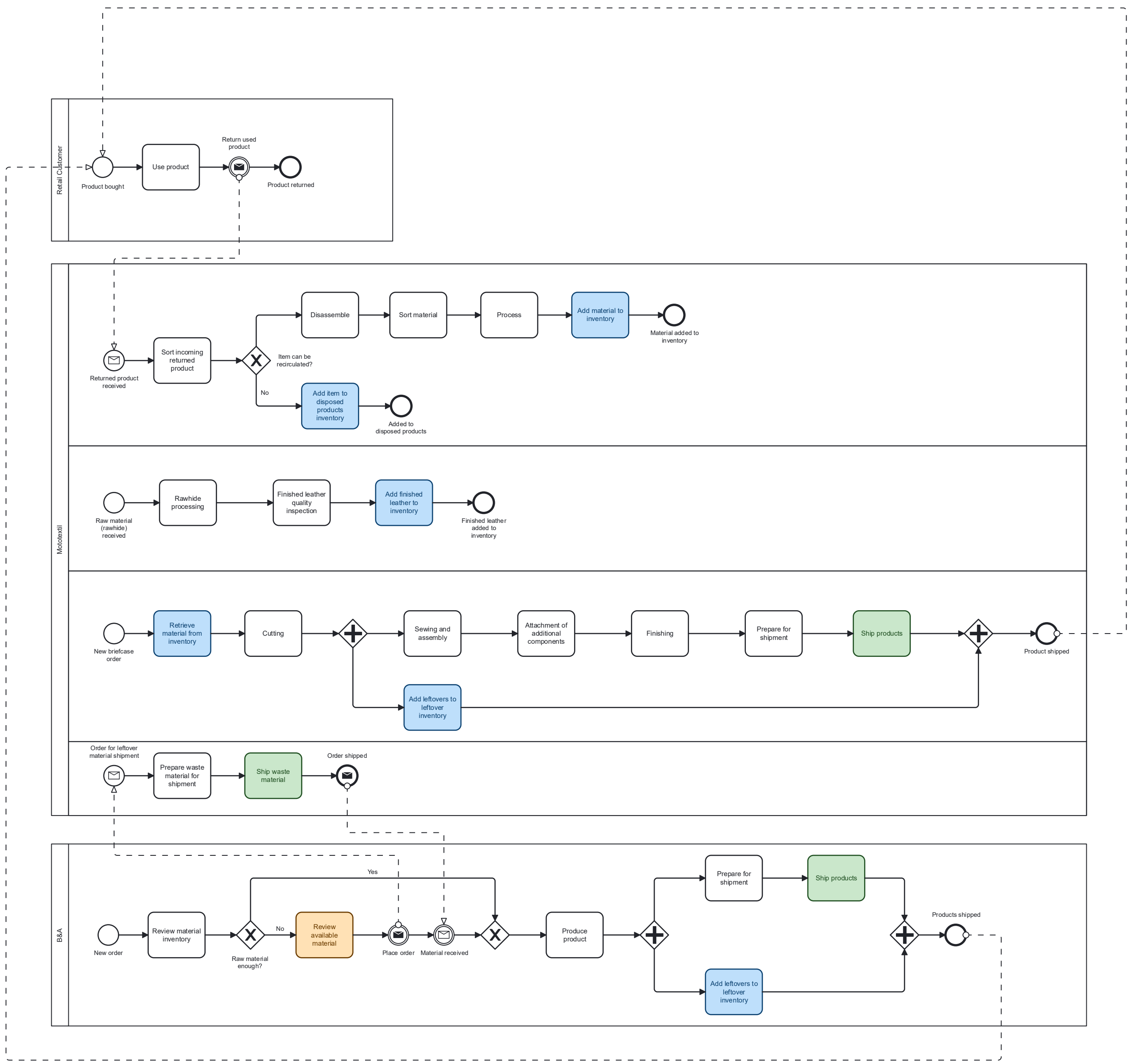

Figure 16 BPMN model for the Leather Pilot - TO-BE

Process Orchestrator and explanation of processes

The overall process includes 3 actors:

- RETAIL CUSTOMER: The retail customer opens and closes the circular overall process. It buys the product and, after using it, returns it to Mototextil.
- MOTOTEXTIL: Mototextil has 4 parallel processes: 1) One is for the reception of used bags, where they are sorted, processed, and material is either added to the inventory for reuse, when possible, or they are put in the disposed products inventory. 2) Another process is for receiving and

processing rawhide and then adding it to the inventory. 3) The main production process includes the receipt of material from the inventory and the production of the bag. During this process, the leftover material (leather) is produced and added to the leftovers inventory. 4) One last process is included, related to the preparation and shipping of the leftovers.

- B&A: B&A has one main production process. It starts by reviewing the available material when an order is received. When it is not enough to fulfil the order, the leftovers of Mototextil are ordered and used for production. Also, during this production, further leftover leather is produced and added to the inventory. That means that even when using the leftovers of Mototextil, during the B&A production, leftover of these leftovers is generated and made available for other manufacturers.

LCA scenario modelling

In order to model the related scenario for making an LCA study, a simplified version of the process was made to identify the reference product(s), system boundaries and inputs and outputs for each process. Figure 17 illustrates the TO-BE scenario, where the reference product is the following:

- **leather bag**, of a weight of 2 kg, produced from virgin finished leather (after the tanning process)
- **leather keyholder** of a weight of 0,6 kg, produced from the leftovers coming from the production of the leather bag

The flow diagrams and associated LCA models are, in this case, different from each other since the leather keyholder is not produced with the leftovers of the bag.

In this case, allocation is required in order to distribute the environmental impacts associated with leather production from the animal among its different co-products (meat and raw hide in this scenario). Allocation is a method used in LCA when several outputs result from a single process, ensuring that the environmental burdens are fairly assigned to each product. The allocation factor for rawhide, obtained from the literature (De Rosa-Giglio et al., 2018), is 0,035. This means that 3.5% of the total impacts from livestock to slaughtering are allocated to leather, with the remaining impacts assigned to meat.

Furthermore, since this involves a multi-product system with material reuse, an additional allocation factor is required to account for the impact of producing the finished leather for the keyholder (leftover).In particular, the allocation method applied is economic allocation, which distributes the environmental impacts of a process based on the relative market value of each co-product. The allocation factor is therefore calculated from the market selling price of each item produced (bag: 200€, keyholder: 20€). This approach reflects the principle that products with higher economic value should bear a proportionally larger share of the environmental burdens, making it a widely used method in LCA when dealing with multi-product systems (Pachón et al. 2018).

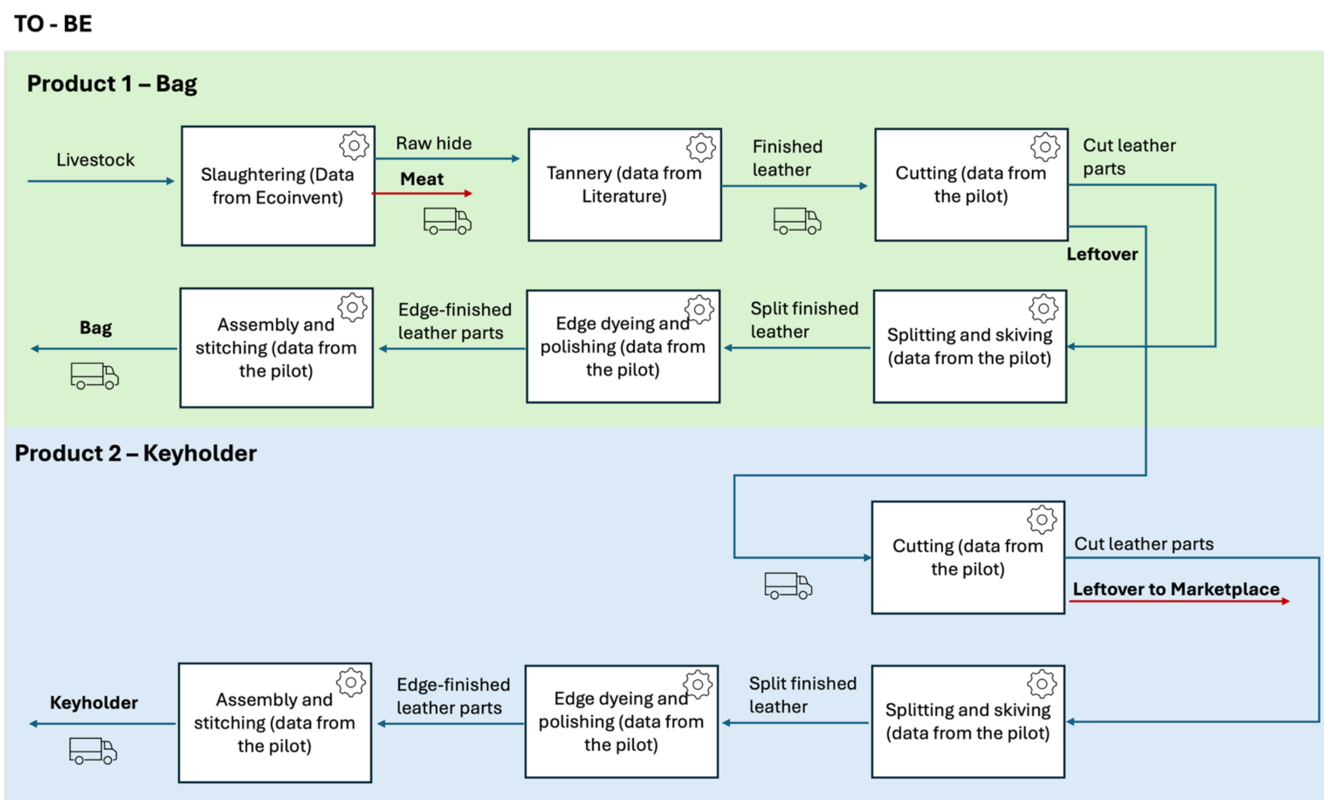

Figure 17 Leather Pilot LCA Model — TO BE Flow Diagram

CIRCULOOS Data Platform

The CIRCULOOS Data Platform facilitates the sharing of the data related to the following kinds of material:

1. Reusable processed leather (recycled)
2. Reusable processed leather (leftover)
3. Disposed products
4. Processed raw leather

Supply Chain Digital Twin (SCDT)

The SCDT has been implemented to model the intra-factory logistics of the companies involved in the leather pilot: Mototextil and B&A, as well as to determine the interconnections between the factories along with the suppliers/consumers of the leather pilot. Based on the detailed description of the processes, input/output materials, scraps and suppliers included in SCDT template, two flow diagrams have been constructed, one for each partner of the leather pilot. As captured by the SCDT template, Figure 18 illustrates the workflow of B&A and Figure 19 illustrates the workflow of Mototextil. Detailed description of the SCDT can be found in the deliverable D3.4 3D Digital Twin of supply chain/production/products M24.

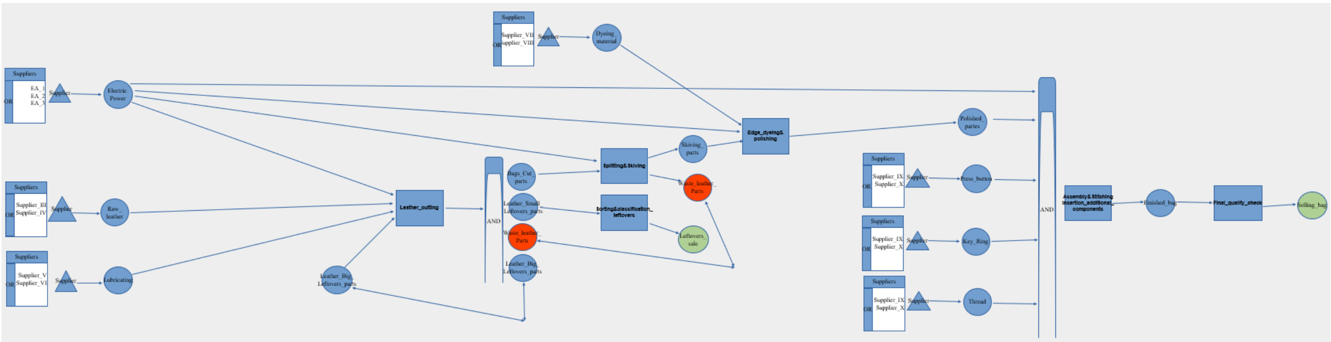

Figure 18: Workflow diagram of B&A in SCDT template.

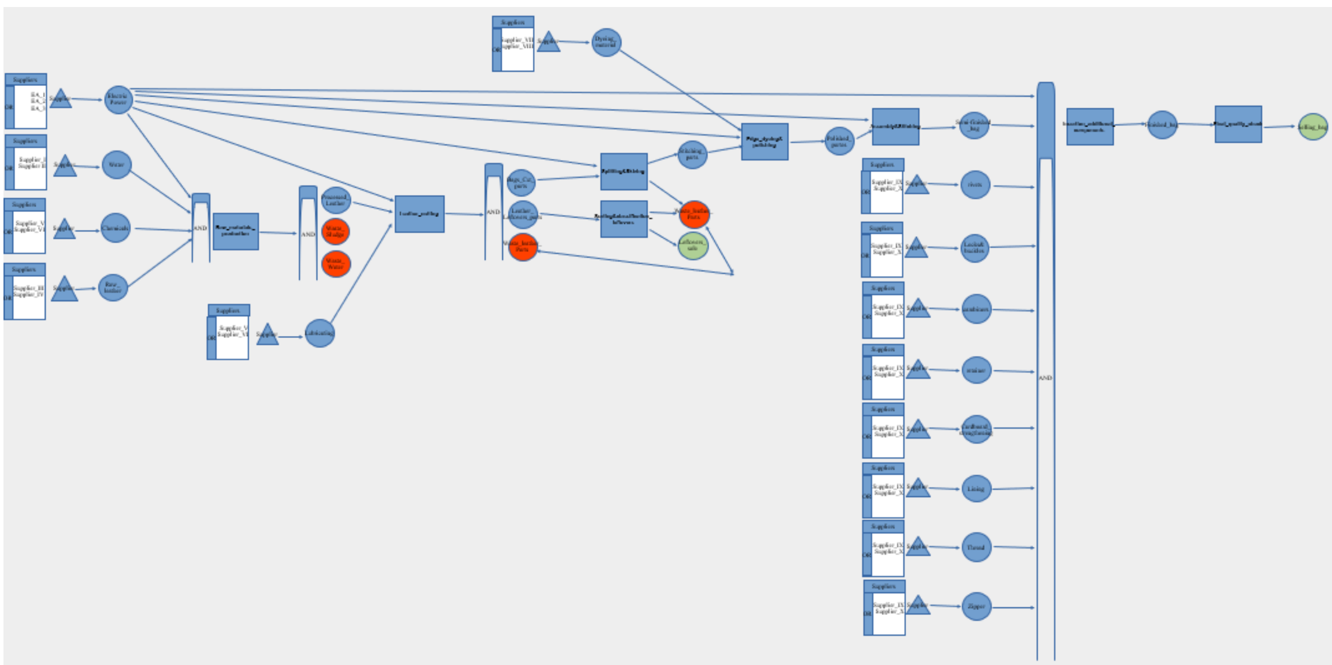

Figure 19: Workflow diagram of Mototextil in SCDT template.

Supply Chain Optimization (SCOPT)

The SCOPT component has been implemented in an intra-factory logistics scenario motivated by the CIRCULOOS leather pilot. The scenario was focused on a part of sewing workflow in order to determine when (or whether) the factory or a part of the workflow will run out of a specific material in order to prevent disruptions in the supply chain. In this scenario, SCOPT has provided a scheduling plan that resolves potential disruptions in the supply chain. Detailed description of the SCOPT implementation can be found in the deliverable D3.8 AI and Data-driven Supply Chain Optimisation M24.

2.3 Life Cycle Inventory

To conduct an LCA, it is essential to first establish a comprehensive global mass and energy balance of the process under study. This involves collecting detailed data on energy requirements, including both heat and electricity consumed throughout the process, as well as all input materials used in the manufacture of the product. Such information forms the basis of the LCI, which is a detailed compilation of all inputs and outputs associated with a product system over its life cycle. The LCI captures the quantities of raw materials, energy flows, emissions to air, water, and soil, and waste generated, serving as the foundation for subsequent environmental impact analysis.

A functional unit is defined for each pilot scenario to ensure consistency and comparability across the study. This functional unit serves as the reference measure to which all inputs and outputs are normalized, enabling a fair comparison of environmental performance between different scenarios. By applying all collected data consistently to this functional unit, the LCA can yield meaningful results. Detailed information on all variables and datasets used in the LCI for this study can be found in Deliverable 3.6, ensuring transparency and reproducibility of the analysis.

In this section, a brief overview of how the LCI was developed for each pilot scenario will be provided. The objective is to give a general understanding of the methodology and data sources used, while a more detailed description of the LCI for each pilot, including all calculations and assumptions, is presented in Deliverable 3.6. This approach allows readers to grasp the core structure of the inventory process without losing sight of the more comprehensive data and methodological details that are documented elsewhere. By outlining the main steps taken to construct the LCI, this section sets the stage for understanding the subsequent life cycle impact assessment and the comparative results between scenarios.

2.4 GRETA: LCA tool

GRETA is a web-based, microservices-driven application designed to assess the sustainability and circularity performance of products and processes in manufacturing contexts. It provides both diagnostic and advisory functionalities, helping users optimize manufacturing practices and make data-driven decisions. Tailored for manufacturing companies focused on sustainable early-stage product design, GRETA enables users to generate and compare different production and usage scenarios, even when only limited data is available during the preliminary design phase. It evaluates the sustainability performance of products and processes, showing how impacts are distributed across different life cycle phases.

GRETA allows end-users to customize production processes modeled by sustainability experts, providing specific values needed for LCA analysis. Once customization is complete, the assessment can be executed, delivering valuable insights through interactive charts. Beyond assessing individual products, GRETA enables comparisons between different products and process alternatives—an essential feature for eco-design (Gnansounou et al, 2015). It also allows manufacturers to compare multiple products using a radar chart. Thanks to its real-time calculation engine, manufacturers can adjust scenario parameters during the eco-design process to optimize impacts and compare results against previous setups or alternative scenarios. The assessment results, including comparisons, can be automatically compiled into a PDF report, summarizing all alternatives, sustainability parameters, and indicators generated by the analysis.

3 Results

This section aims to showcase the results concerning environmental benefits and technical KPIs, in order to evaluate the advantages that the CIRCULOOS approach may offer to the consortium pilots. It serves both as evidence to assess the functionalities and the CE practices applied to the pilots, and as guidelines for future approaches and the implementation of similar tools in the Open Call experiments.

3.1 Wood Pilot

In the framework of the wood pilot, the selected functional unit for the LCA is defined as the production of one CLT panel.

In the AS IS scenario, the CLT panel is produced using virgin wood sourced from European forests, while electricity is generated from damaged ornamental trees collected in the city of Rotterdam by PLENNID. In the TO BE scenario, the wood panel is instead produced from the damaged ornamental trees of Rotterdam, while the trees in the forest remain unharvested.

Two production scenarios were analyzed to evaluate potential improvements in environmental performance:

- **AS-IS scenario**: represents the current situation, where 100% virgin wood is used as feedstock for CLT production, and electricity is generated from the damaged ornamental trees of Rotterdam.
- **TO-BE scenario**: represents the proposed future situation, in which the damaged trees are repurposed as feedstock for wood panel production, while electricity is generated in compliance with the Dutch electricity mix.

The recycled material used in the TO-BE configuration is supplied by Plennid and HERSO, the project partners responsible for collecting damaged trees to produce reclaimed wood and manufacturing the wood panels from this reclaimed wood, respectively.

The overall objective of this pilot is to assess the environmental benefits of integrating reclaimed wood into the Circuleren supply chain, thereby promoting a more circular and resource-efficient production model. The analysis focuses on quantifying potential reductions in environmental impacts resulting from the complete substitution of virgin wood with urban wood.

The comparative LCA has been performed in accordance with the principles and framework established by ISO 14040 and ISO 14044. Both scenarios were modelled using the OpenLCA open source software prior to their implementation in GRETA. In OpenLCA, the LCI variables were defined based on primary data provided by project partners, complemented with secondary data from the Ecoinvent database where necessary. The models represent the material and energy flows across all relevant life cycle stages of the wood panel production process.

Once completed, both models were integrated into the GRETA platform for simulation and comparative analysis. Figure 20 illustrates the two LCA models implemented in GRETA. This integration enables a dynamic and visual evaluation of environmental performance across the defined scenarios, supporting interpretation and decision-making by industrial partners.

Both the AS IS and TO BE scenarios were assessed from an environmental perspective to calculate their respective impact indicators associated with the production of one wood panel. Through GRETA, the comparative results highlight the differences between the current production setup—entirely dependent on virgin wood—and the proposed configuration, which incorporates 100% reclaimed wood, leaving the forest trees untouched.

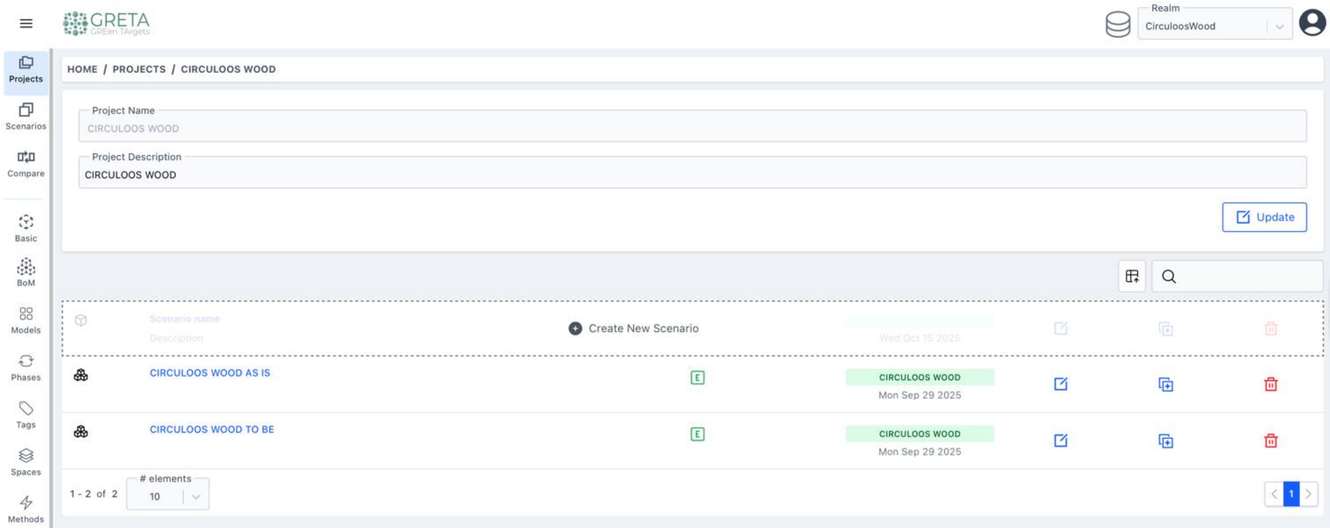

Figure 20 AS IS and TO BE scenarios for the wood pilot in GRETA.

Figure 21 and Table 1 present the comparative outcomes of the assessment. As expected, the TO BE scenario (red in the chart) shows improvements across several environmental indicators, confirming the potential advantages of integrating reclaimed wood into the wood pilot production process, compared to the AS-IS scenario (in green in the chart – representing 100% of the indicators' value).

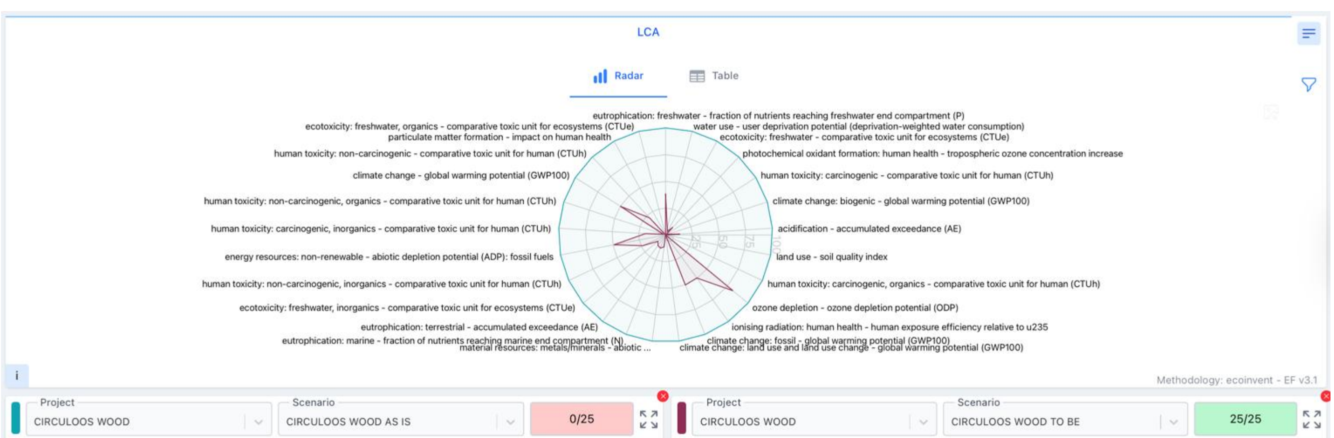

Figure 21 Comparative LCA results in Wood Pilot (generated in GRETA)

Impact Category	**Unit**	**AS IS**	**TO BE**	**Variation (%)**
Climate change (GWP100)	kg CO_2-eq	1.64×10^{2}	8.23×10^{1}	−49.9%
Climate change – biogenic (GWP100)	kg CO_2-eq	5.79×10^{-1}	1.33×10^{-2}	−97.7%
Climate change – land use & LUC (GWP100)	kg CO_2-eq	2.80×10^{-1}	-7.99×10^{-2}	−128.5%
Acidification (AE)	mol H^+-eq	8.59×10^{-1}	1.16×10^{-1}	−86.5%
Eutrophication – freshwater	kg P-eq	6.38×10^{-2}	2.46×10^{-2}	−61.4%

Eutrophication – marine	kg N-eq	2.42×10^{-1}	3.20×10^{-2}	−86.8%
Eutrophication – terrestrial (AE)	mol N-eq	2.69×10^{0}	3.26×10^{-1}	−87.9%
Photochemical oxidant formation (human health)	kg NMVOC-eq	9.59×10^{-1}	9.42×10^{-2}	−90.2%
Particulate matter formation	disease incidence	1.65×10^{-5}	-2.72×10^{-6}	−116.5%
Ozone depletion (ODP)	kg CFC-11-eq	3.37×10^{-6}	2.75×10^{-6}	−18.4%
Ionising radiation (human health)	kBq U^{235}-eq	1.37×10^{1}	6.81×10^{0}	−50.3%
Ecotoxicity – freshwater (total)	CTUe	9.54×10^{2}	3.65×10^{1}	−96.2%
Ecotoxicity – freshwater, inorganics	CTUe	6.45×10^{2}	5.99×10^{1}	−90.7%
Ecotoxicity – freshwater, organics	CTUe	3.09×10^{2}	-2.35×10^{1}	−107.6%
Human toxicity – carcinogenic (total)	CTUh	1.06×10^{-6}	1.06×10^{-8}	−99.0%
Human toxicity – carcinogenic, organics	CTUh	1.02×10^{-6}	2.38×10^{-9}	−99.8%
Human toxicity – carcinogenic, inorganics	CTUh	4.31×10^{-8}	8.20×10^{-9}	−81.0%
Human toxicity – non-carcinogenic (total)	CTUh	2.13×10^{-6}	4.67×10^{-7}	−78.1%
Human toxicity – non-carcinogenic, inorganics	CTUh	1.97×10^{-6}	4.63×10^{-7}	−76.5%
Human toxicity – non-carcinogenic, organics	CTUh	1.58×10^{-7}	3.80×10^{-9}	−97.6%
Material resources – metals/minerals (ADP)	kg Sb-eq	7.99×10^{-4}	9.01×10^{-5}	−88.7%
Energy resources – non-renewable (ADP fossil fuels)	MJ (NCV)	2.63×10^{3}	1.30×10^{3}	−50.6%
Water use – deprivation-weighted consumption	m^3 world-eq deprived	1.18×10^{2}	7.62×10^{0}	−93.5%
Land use – soil quality index	dimensionless	1.89×10^{4}	-7.69×10^{3}	−140.7%

Table 1 Comparative LCA results in Wood Pilot (generated in GRETA)

The comparative LCA results clearly demonstrate an overall environmental improvement in the TO BE scenario compared to the AS IS configuration. By replacing virgin wood with urban wood from damaged city trees, most impact categories show substantial reductions, particularly those linked to resource extraction and energy use. The Global Warming Potential - GWP indicator shows a decrease of nearly 50%, from 164.5 kg CO_2-eq in the AS IS scenario to 82.2 kg CO_2-eq in the TO BE scenario, confirming a significant mitigation of greenhouse gas emissions (Figure 22). This reduction is mainly attributed to the avoidance of virgin wood harvesting and processing, along with the use of the Dutch electricity mix instead of biomass-based generation. Overall, the integration of reclaimed wood into wood panel production demonstrates clear potential to enhance circularity and lower the environmental footprint of the wood pilot.

Figure 23 shows some negative contributions appear within the GWP results in the TO BE scenario. These represent environmental credits associated with leaving the trees in the forest rather than harvesting them. By avoiding tree removal, carbon remains stored in the standing biomass and continues to be sequestered over time, resulting in a net negative CO_2 balance. This credit effectively offsets part of the emissions generated during manufacturing and energy use, highlighting the climate benefit of preserving forest carbon stocks while utilizing reclaimed urban wood as a circular material source.

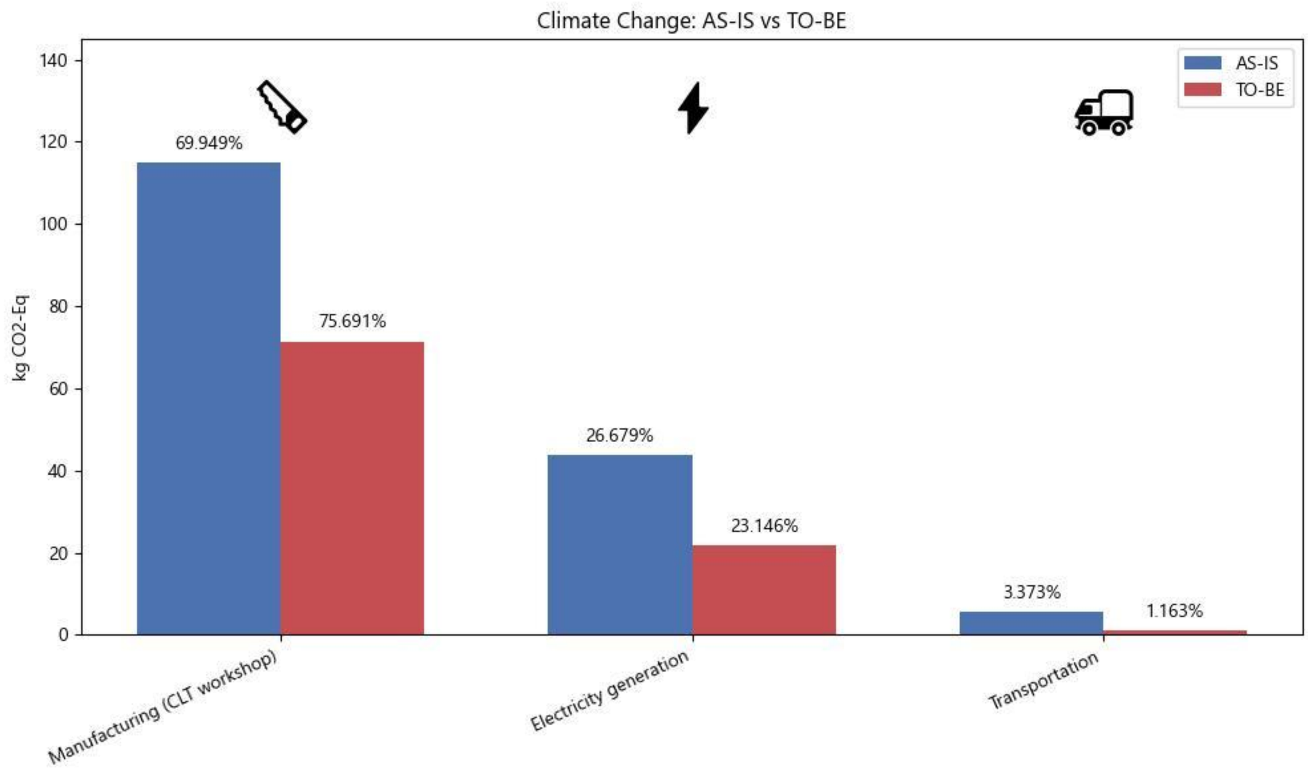

Figure 22 Distribution of GWP across Life Cycle Stages for AS-IS and TO-BE wood pilot scenarios

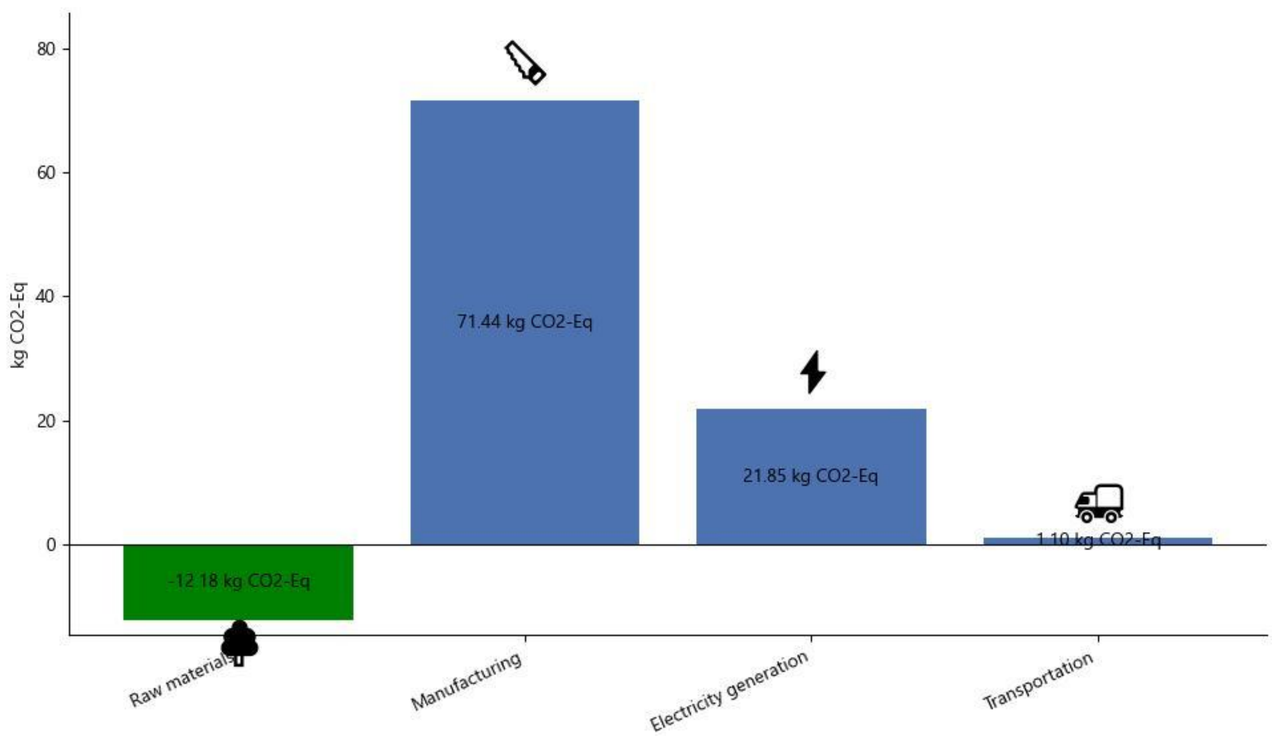

Figure 23 The GWP indicator across the Life Cycle Stage in the TO-BE Wood Pilot scenario

KPIs evaluation

The following complementary KPIs have been defined together with the Wood Pilot partners Circu-leren, Herso, and Plennid to monitor the environmental and resource-related benefits of circular wood flows.

These indicators focus on material circularity and carbon footprint reduction at product and value chain level, comparing AS IS and TO BE configurations.

KPI Name	Description	Unit of Measurement	Partner(s)	Value	Benchmark (from DoA)
CO_2 savings by buying ornamental threes compared to virgin CLT (sustainability gain)	Avoided CO_2 emissions achieved by purchasing ornamental threes instead of virgin Cross-Laminated Timber (CLT) panels.	%(kg CO_2-eq / FU)	Circu-leren	≈ 50%	≥25%
CO_2 saved by not importing wood	Reduction of CO_2 emissions obtained by sourcing local wood instead of imported materials.	kg CO_2-eq / FU	Plennid	3.02*	N/A
Cost reduction	Reduction in percentage of the final product by using urban timber as raw material	%(€)	Circu-leren	47,2%	30%
Energy saving	Energy saving due to process optimization. Production of wood scrap represents energy expenditure. This can be minimized though optimized supply chain arrangements.	% (kWh)	Plennid and Circuleren	15%-25% represents the average wood scrap production rate.	10%

Table 2 Wood pilot KPIs

* This KPI estimates the amount of CO_2 emissions avoided by sourcing local urban wood instead of importing virgin timber from abroad. The calculation considers two main contributions: the emissions avoided from long-distance transport and the environmental credit associated with leaving forest trees uncut.

For the transport component, the AS IS scenario includes a long import route from Berlin to Beverwijk (approximately 690 km) for a 38.5 kg CLT panel, corresponding to a transport activity of 2.66×10^4 kg·km. Using a standard emission factor for heavy-duty trucks (0.1 kg CO_2 per ton·km), this route results in about 2.66 kg CO_2 per panel. In the TO BE scenario, this international transport is completely avoided, as the wood is sourced locally from Rotterdam. Therefore, this part of the KPI corresponds to a saving of 2.66 kg CO_2 per panel.

The second contribution comes from forest preservation. In the TO BE configuration, the use of urban trees means that no new trees are harvested from forests, allowing the carbon stored in standing biomass to remain sequestered. This benefit is represented in the LCA results as a negative contribution in the category Climate change – land use & LUC (GWP100), equal to approximately 0.36 kg CO_2-eq per panel.

Combining these two effects, the overall benefit of sourcing local urban wood instead of importing virgin timber amounts to an estimated 3.02 kg CO_2-eq saved per functional unit (wood panel).

Supply Chain Digital Twin (SCDT)

Utilizing the data provided in the SCDT templates of the wood pilot, one model per factory has been constructed in SCDT as well as the interconnections between the factories representing the supply chain arrangement of the wood pilot. The supply chain model of the wood pilot developed in SCDT is shown in Figure 24, the factory model of Circuleren is shown in Figure 25, the factory model of Herso is shown in Figure 26 and the factory model of Plennid is shown in Figure 27. Detailed description of the SCDT implementation can be found in the deliverable D3.4 3D Digital Twin of supply chain/production/products M24.

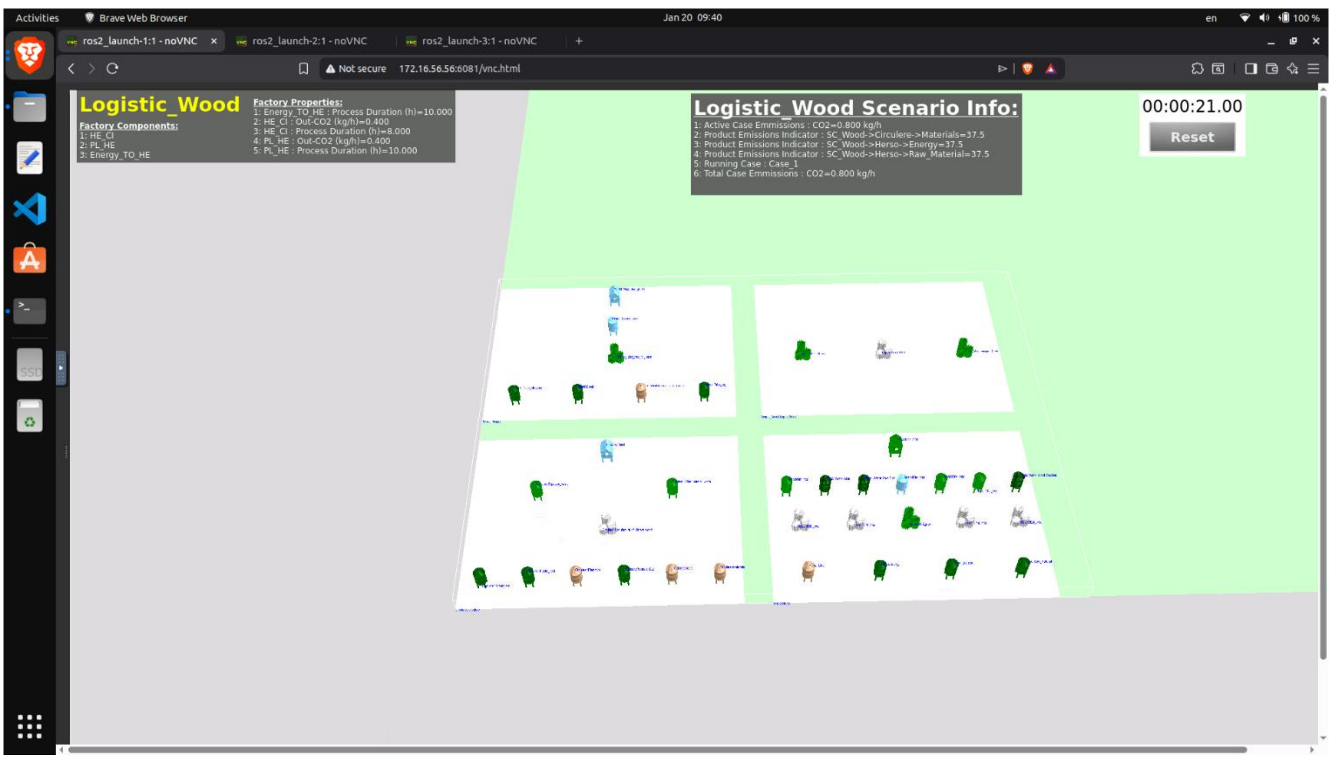

Figure 24: Supply chain model of the wood pilot in SCDT.

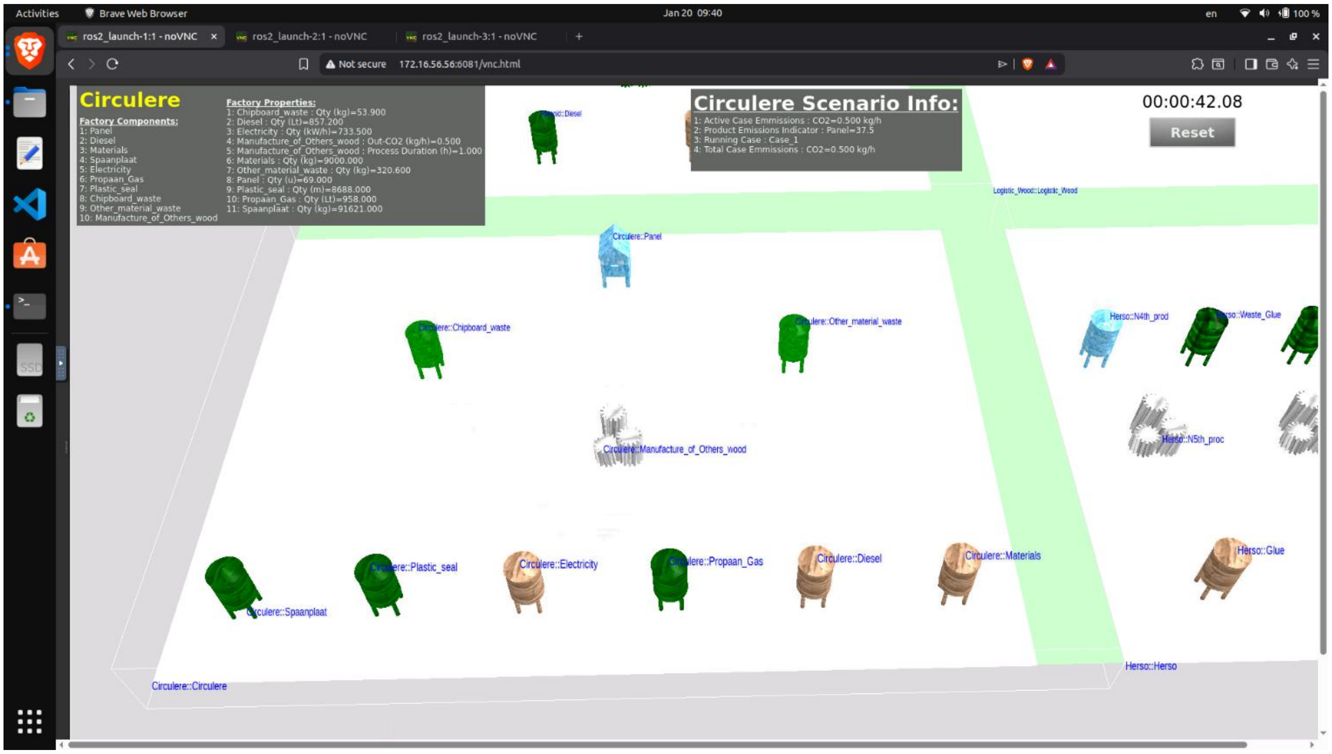

Figure 25: Model of Circulere factory in SCDT.

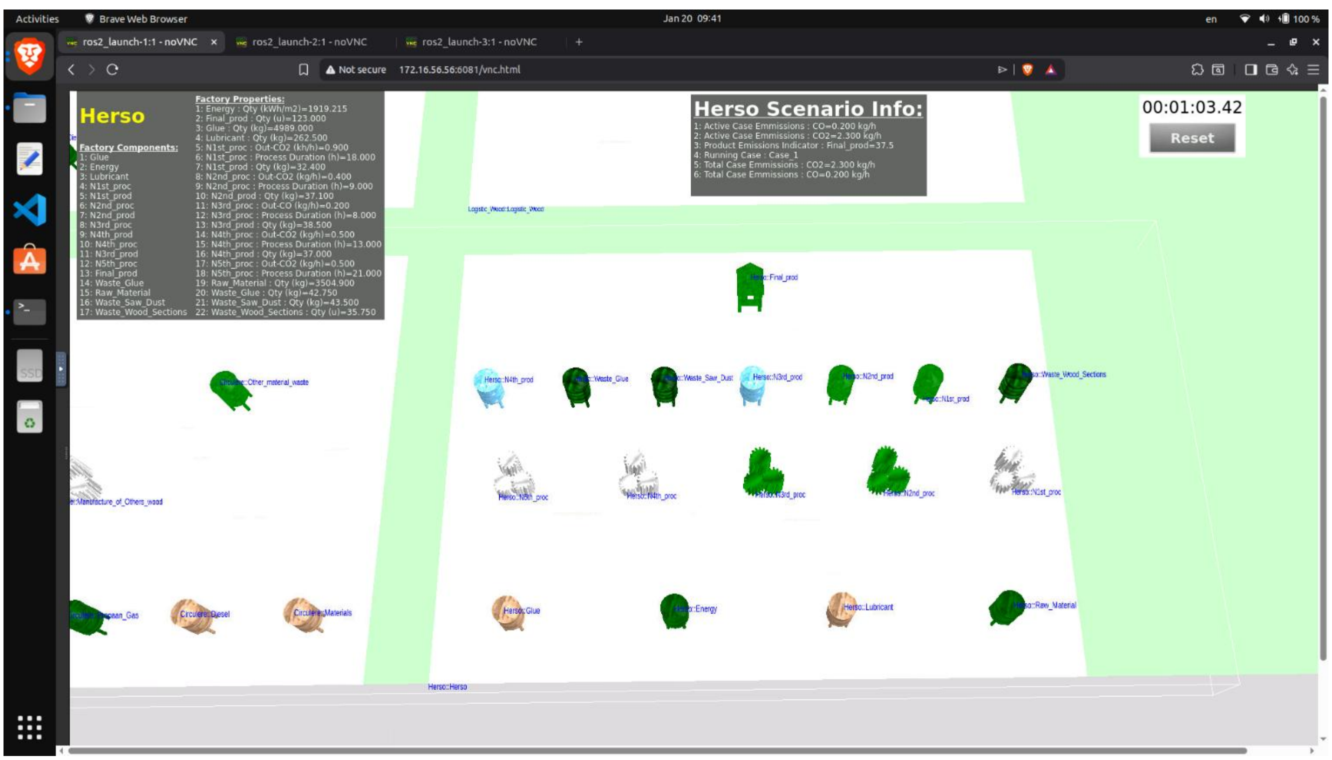

Figure 26: Model of Herso factory in SCDT.

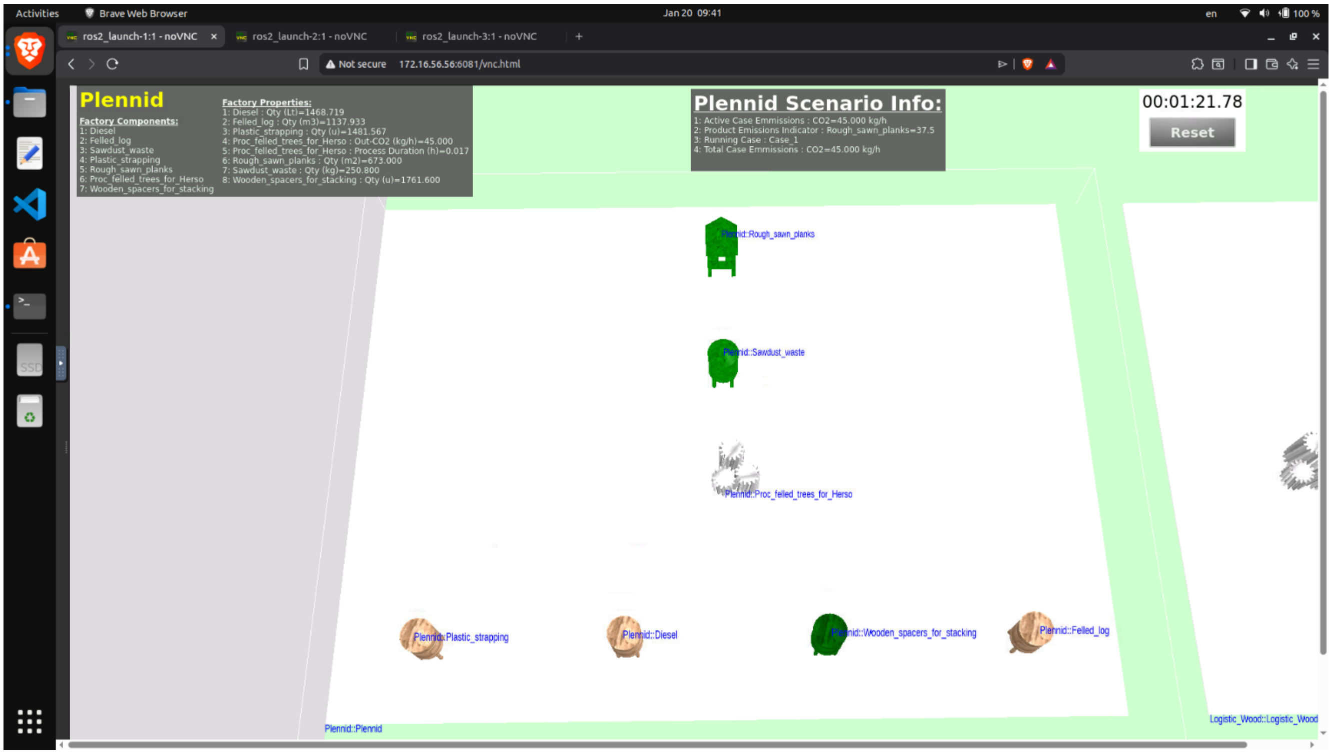

Figure 27: Model of Plennid factory in SCDT.

Supply Chain Optimization (SCOPT)

The SCOPT module is leveraged to provide a feasible solution to a scenario that maintains a core of three companies in a supply chain, motivated by the wood pilot case, while exploring the benefits of possibly including additional companies in the supply chain in order to reduce the wood scrap. An abstraction model of the supply chain has been constructed to model the key features of the supply chain and the resulting model abstraction was implemented on the SCOPT tool. A scenario has been investigated to find the supply chain arrangement to eliminate the wood scrap produced and produce new products from recycled wood scrap or recycled wood materials while keeping the current supply chain arrangement of the wood pilot as the core of the proposed supply chain. Utilizing SCOPT, the supply chain arrangement provided engaging the main Factories of the supply chain (HERSO, Plennid and Circuleren) while introducing Factory D and Factory E to recycle the scrap produced by HERSO, Plennid and Circuleren in order to produce new products from recycled scrap. The detailed presentation of the results for the wood pilot provided by SCOPT is described in *D3.8 "AI and Data-driven Supply Chain Optimisation M24"*.

Additionally, based on the LCA results presented in Table 1 showing the significant reduction of Global Warming Potential by 50% in case of replacing virgin wood with urban wood from damaged city trees, an alternative scenario that can be investigated with SCOPT when alternative urban wood suppliers become available, would be to determine the appropriate mixture of urban and virgin wood supply in order to ensure a stable supply chain while minimizing the Global Warming Potential.

3.2 Plastic Pilot

In the framework of the plastic pilot, the selected functional unit for the LCA is defined as the production of a single washing machine detergent dispenser. This dispenser is composed of five individual components: four made of white plastic and one made of blue plastic, corresponding to the siphon. The white plastic parts form the main body and outer structure of the dispenser, while the blue siphon serves as an internal functional element essential for detergent dosing. It is important to note that no waste related to the blue siphon is generated within Thermolympic's production processes.

Two production scenarios were analyzed to evaluate potential improvements in environmental performance:

- AS IS scenario: representing the current situation, in which 100% virgin plastic is used as feedstock for all five components of the dispenser.
- TO BE scenario: representing the proposed future situation, in which 50% recycled plastic is incorporated into four of the five dispenser components (the white plastic parts), while the siphon continues to be produced from virgin blue plastic.

The recycled material used in the TO BE configuration is supplied by Contenedores LOLO, a partner responsible for producing high-quality recycled granulate. This recycled plastic originates from post-industrial waste streams, including Thermolympic's own production waste, as well as additional plastic residues collected free of charge from external waste suppliers.

The overall objective of this pilot is to assess the environmental benefits of integrating recycled materials into Thermolympic's supply chain, promoting a more circular and resource-efficient production model. The analysis focuses on quantifying potential reductions in environmental impacts, such as resource depletion, energy consumption, and greenhouse gas emissions, resulting from partial substitution of virgin material with recycled plastic.

The comparative LCA has been performed in accordance with the principles and framework established by the ISO 14040 and ISO 14044 standards. Both scenarios were modelled using the OpenLCA open source software prior to their implementation in GRETA. In OpenLCA, the LCI variables were defined based on primary data provided directly by the project partners, complemented with secondary data from the Ecoinvent database whenever necessary. The models were constructed to represent material and energy flows across all relevant life cycle stages of the dispenser's production process.

Once completed, both models were integrated into the GRETA platform for simulation and comparative analysis. Figure 28 illustrates the two LCA models implemented in GRETA. This integration enables a dynamic and visual evaluation of environmental performance across the defined scenarios, facilitating interpretation and decision-making for industrial partners.

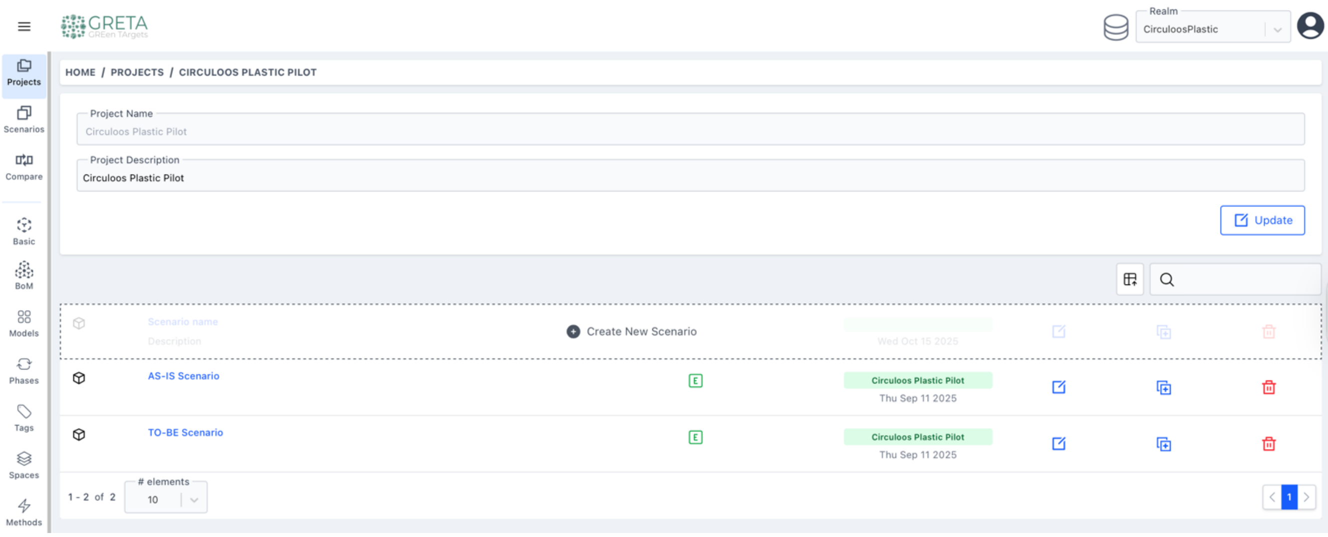

Figure 28 AS IS and TO BE scenarios for the plastic pilot in GRETA

Both the AS IS and TO BE scenarios were assessed from an environmental perspective in order to calculate their respective impact indicators associated with the production of one washing machine detergent dispenser. Through GRETA, the comparative results highlight the differences between the current production setup, entirely dependent on virgin plastic, and the proposed configuration incorporating 50% recycled plastic.

Figure 29 and Table 3 present the comparative outcomes of the assessment. As expected, the TO BE scenario demonstrates an improvement in several environmental categories, confirming the potential benefits of integrating recycled plastic into Thermolympic's production process.

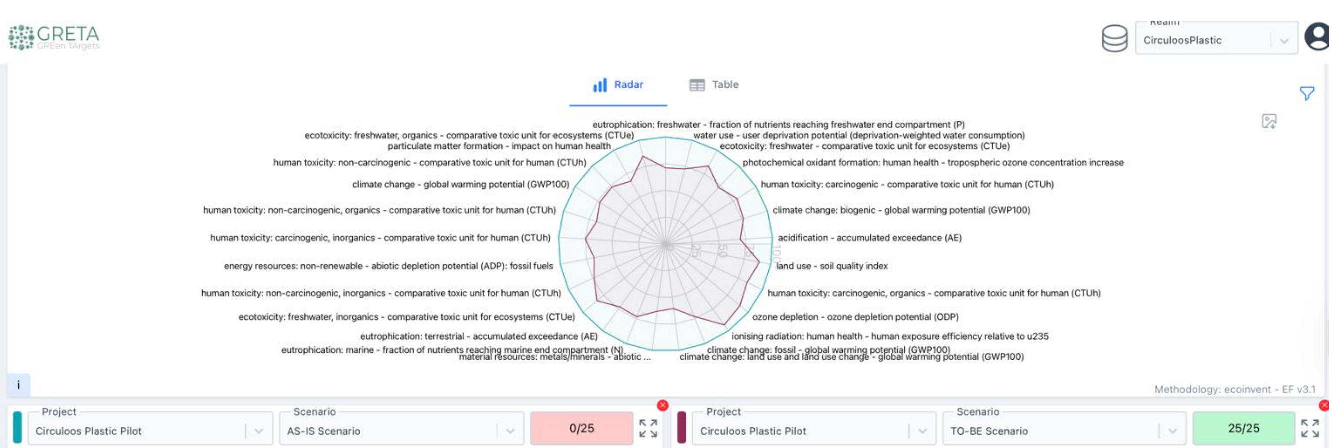

Figure 29 Comparative LCA results in Plastic Pilot (generated in GRETA)

Impact Category	Unit	AS IS	TO BE	Variation (%)
Climate change (GWP100)	kg CO_2-eq	1.79×10^{0}	1.30×10^{0}	**−27.4%**
Climate change – biogenic (GWP100)	kg CO_2-eq	2.98×10^{-3}	2.28×10^{-3}	**−23.5%**

Climate change – land use & LUC (GWP100)	kg CO_2-eq	1.15×10^{-3}	6.97×10^{-4}	**−39.4%**
Acidification (AE)	mol H^+-eq	6.35×10^{-3}	4.44×10^{-3}	**−30.1%**
Eutrophication – freshwater	kg P-eq	2.33×10^{-4}	1.66×10^{-4}	**−28.8%**
Eutrophication – marine	kg N-eq	1.29×10^{-3}	9.44×10^{-4}	**−26.8%**
Eutrophication – terrestrial (AE)	mol N-eq	1.35×10^{-2}	9.78×10^{-3}	**−27.6%**
Photochemical oxidant formation (human health)	kg NMVOC-eq	6.28×10^{-3}	4.55×10^{-3}	**−27.6%**
Particulate matter formation	disease incidence	6.25×10^{-8}	4.19×10^{-8}	**−33.0%**
Ozone depletion (ODP)	kg CFC-11-eq	4.01×10^{-8}	3.61×10^{-8}	**−10.0%**
Ionising radiation (human health)	kBq U^{235}-eq	3.73×10^{-1}	3.48×10^{-1}	**−6.7%**
Ecotoxicity – freshwater (total)	CTUe	4.42×10^{0}	3.67×10^{0}	**−17.0%**
Ecotoxicity – freshwater, inorganics	CTUe	4.03×10^{0}	3.35×10^{0}	**−16.9%**
Ecotoxicity – freshwater, organics	CTUe	3.87×10^{-1}	3.28×10^{-1}	**−15.2%**
Human toxicity – carcinogenic (total)	CTUh	6.09×10^{-10}	4.82×10^{-10}	**−20.9%**
Human toxicity – carcinogenic, organics	CTUh	2.76×10^{-10}	2.32×10^{-10}	**−15.9%**
Human toxicity – carcinogenic, inorganics	CTUh	3.33×10^{-10}	2.50×10^{-10}	**−25.0%**
Human toxicity – non-carcinogenic (total)	CTUh	1.17×10^{-8}	8.54×10^{-9}	**−27.0%**
Human toxicity – non-carcinogenic, inorganics	CTUh	1.07×10^{-8}	7.84×10^{-9}	**−26.7%**
Human toxicity – non-carcinogenic, organics	CTUh	1.04×10^{-9}	7.02×10^{-10}	**−32.5%**
Material resources – metals/minerals (ADP)	kg Sb-eq	7.43×10^{-6}	4.71×10^{-6}	**−36.6%**
Energy resources – non-renewable (ADP fossil fuels)	MJ (NCV)	5.52×10^{1}	3.74×10^{1}	**−32.2%**
Water use – deprivation-weighted consumption	m^3 world-eq deprived	7.26×10^{-1}	5.25×10^{-1}	**−27.7%**
Land use – soil quality index	dimensionless	6.94×10^{0}	6.20×10^{0}	**−10.7%**

Table 3 Comparative LCA results in Plastic Pilot (generated in GRETA)

The results show a consistent reduction in environmental impacts across all categories for the TO-BE scenario, which incorporates 50% recycled plastic in four of the five dispenser components, compared to the AS-IS configuration based entirely on virgin material. The most significant improvements were observed in climate change (−27%), non-renewable energy use (−32%), and water consumption (−28%), along with notable decreases in acidification, eutrophication, and human and ecosystem toxicity indicators.

The results of all environmental indicators calculated in GRETA are available for export in CSV format, allowing for in-depth data analysis of each scenario. In this study, in-depth analyses were carried out using Python scripts in Visual Studio Code. In this case, Figure 30 was generated in Python using the results of the Global Warming Potential (GWP) indicator, distributed across the different stages considered in this pilot: downstream transportation (logistics for the transport from Thermolympic to the customer), raw material production, manufacturing (including injection molding for the 5 pieces composing the dispenser, and the recycling step of the TO BE scenario), and upstream transportation (from the supplier to Thermolympic facilities).

It can be observed that, in all cases, raw material production is the stage contributing the most to the environmental impacts associated with the production of one dispenser. First of all, the upstream transportation impacts are reduced in the TO-BE scenario due to the lower quantity of virgin material transported. By reducing the contribution of this stage through the use of recycled materials, a slight increase is observed in the manufacturing stage (since part of the recycling process is included there). Finally, the downstream transportation impact remains identical in both scenarios, as the product is manufactured in Thermolympic and delivered to the same customer. Overall, the reduction of kg CO_2eq achieved in the production of the dispenser using recycled raw materials in the feedstock of Thermolympic is quite significant.

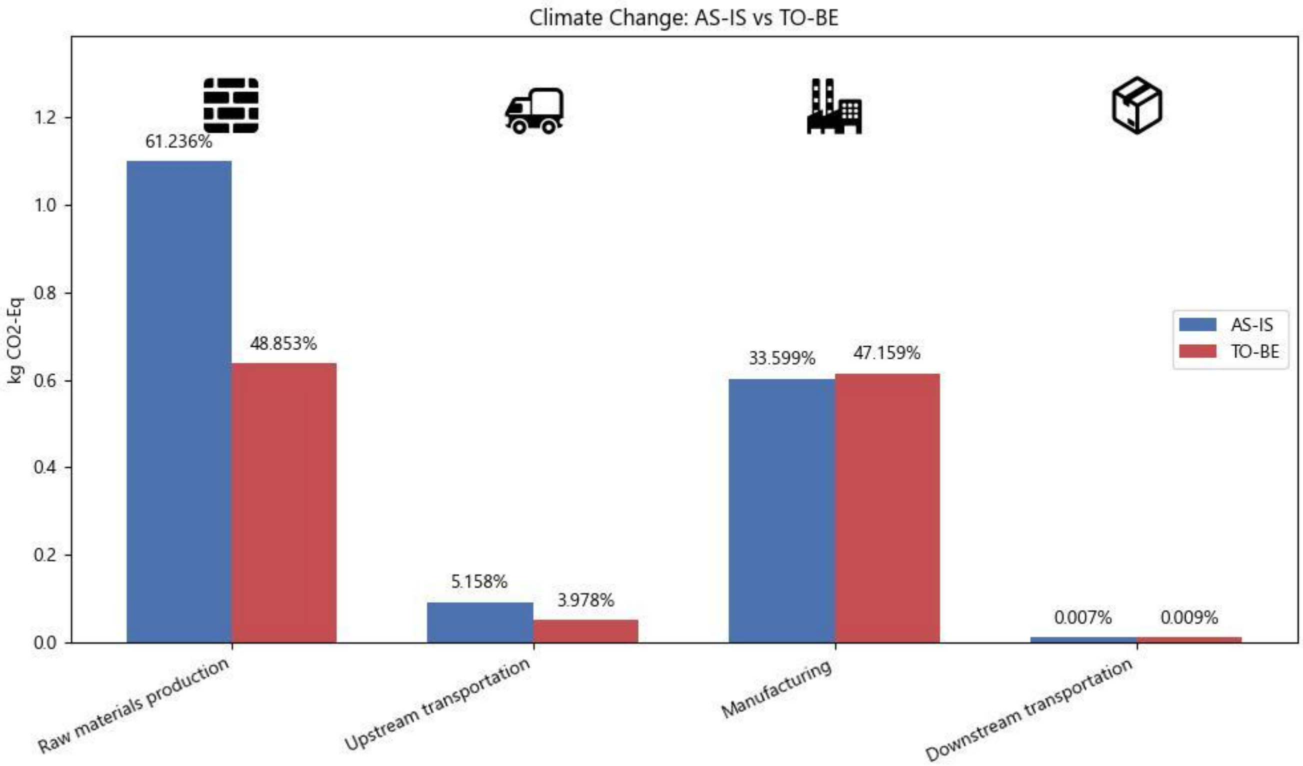

Figure 30 Distribution of GWP across Life Cycle Stages for AS-IS and TO-BE plastic pilot scenarios

Once the comparison has been completed, it is possible to carry out a more comprehensive and in-depth evaluation of the LCA for the proposed alternative. Figure 30 provides a detailed representation of this analysis for the GWP indicator, highlighting the key stages of the dispenser manufacturing process and illustrating where the main contributions to environmental impacts occur. While Figure 30 focuses on the GWP indicator, the same methodology and approach can be applied to all other environmental indicators considered in the assessment, such as water consumption, eutrophication, acidification, and human toxicity, among others. The results for these additional indicators are documented in detail in Deliverable 3.6, providing a comprehensive view of the environmental performance of the proposed solution across multiple impact categories.

In this study, three TO-BE scenarios were analyzed by adjusting the proportion of recycled plastic in the feedstock. As illustrated in the Python-generated Figure 31, higher recycled material content in the production of the washing machine detergent dispenser results in a marked decrease in total GWP, demonstrating the environmental advantages of incorporating recycled plastics into the product design.

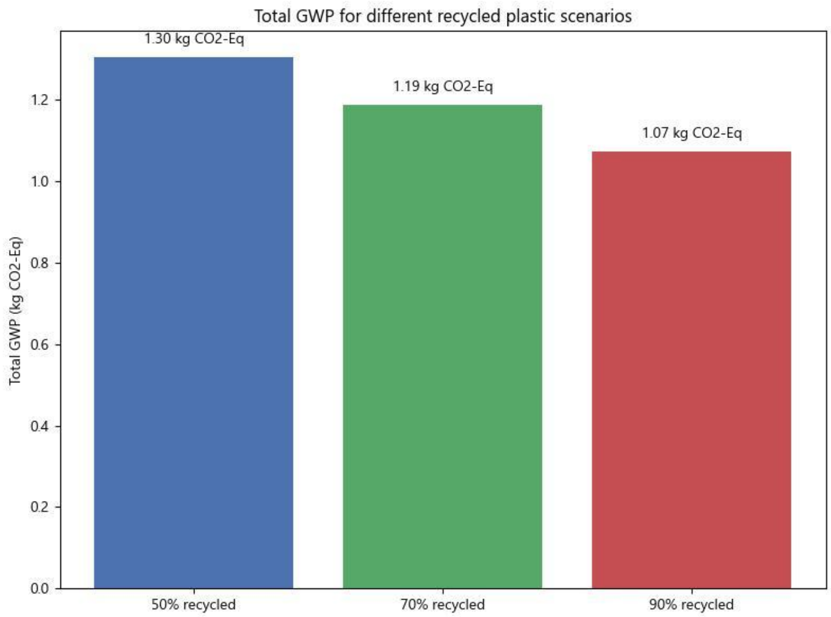

Figure 31 Impact of increasing recycled plastic content on Total GWP in the plastic pilot

In summary, the analysis confirms that no impact category shows any deterioration in performance compared to the baseline scenario, demonstrating that the incorporation of recycled plastic into dispenser production delivers a clear net environmental benefit. Beyond reducing the overall environmental footprint, this approach also supports the implementation of circular economy principles by promoting the use of secondary raw materials and more sustainable production practices throughout the pilot's value chain.

KPIs evaluation

The following KPIs have been defined in collaboration with the Plastic Pilot partners to evaluate the environmental and economic improvements achieved through the adoption of recycled plastics within the CIRCULOOS framework.

These indicators provide a quantitative assessment of circularity, energy efficiency, and cost performance, comparing the AS IS scenario (based on virgin plastic) with the TO BE scenario (based on recycled material).

KPI Name	Description	Unit of Measurement	Partner(s)	Value	Benchmark (from DoA)
Percentage of recycled material	Measures the share of recycled plastic used compared to total material input, indicating the level of circularity achieved in the production process.	% of total material input	Thermolympic	Material 1: 50%, Material 2: 50%, Material 3: 0% (due to not available material)	N/A
CO_2 Emission Reduction	Quantifies the avoided	kg CO_2-eq / FU	Thermolympic	≈ 27%	≥25%

(sustainability gain)	greenhouse gas emissions by replacing virgin plastic with recycled plastic, based on comparative LCA results.				
Production Cost Reduction	Measures the percentage decrease in total production cost per functional unit when using recycled instead of virgin plastic. The cost includes materials, energy, and processing operations.	%(€)	Thermolympic and LOLO	up to 25%*	30%
Energy saving	Energy saving due to process optimization. Unutilized plastic scrap represents energy waste. This can be minimized across the proposed optimized supply chain.	€ (kWh)	Thermolympic	10.5% represents the average scrap rate production	10%

Table 4 Plastic pilot KPIs

* by introducing 50% recycled content for the Hostacom and ISOFIL H50 C2V materials, whose cost is approximately half that of virgin plastic, the average material cost per functional unit decreases by almost 25% compared to the baseline scenario using only virgin materials. In this case, energy consumption and processing operations remain the same between the AS-IS and TO-BE scenarios.

Supply Chain Digital Twin (SCDT)

Utilizing the data provided in the SCDT templates of the plastic pilot, one model per factory has been constructed in SCDT as well as the interconnections between the factories representing the supply chain arrangement of the plastic pilot. The supply chain model of the plastic pilot developed in SCDT is shown in Figure 32, the factory model of Thermolympic is shown in Figure 33 and the factory model of LOLO is shown Figure 34. A detailed description of the SCDT implementation can be found in deliverable D3.4, 3D Digital Twin of supply chain/production/products M24.

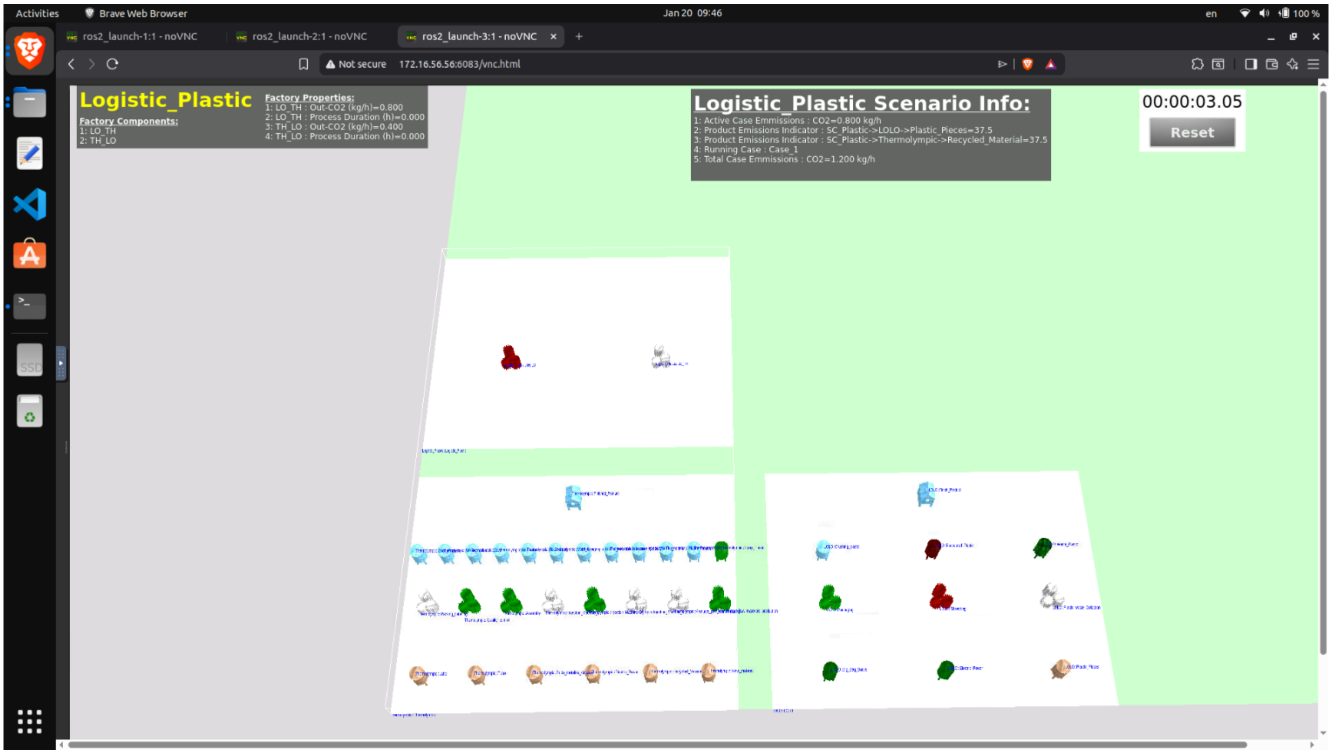

Figure 32: Supply chain model of plastic pilot in SCDT.

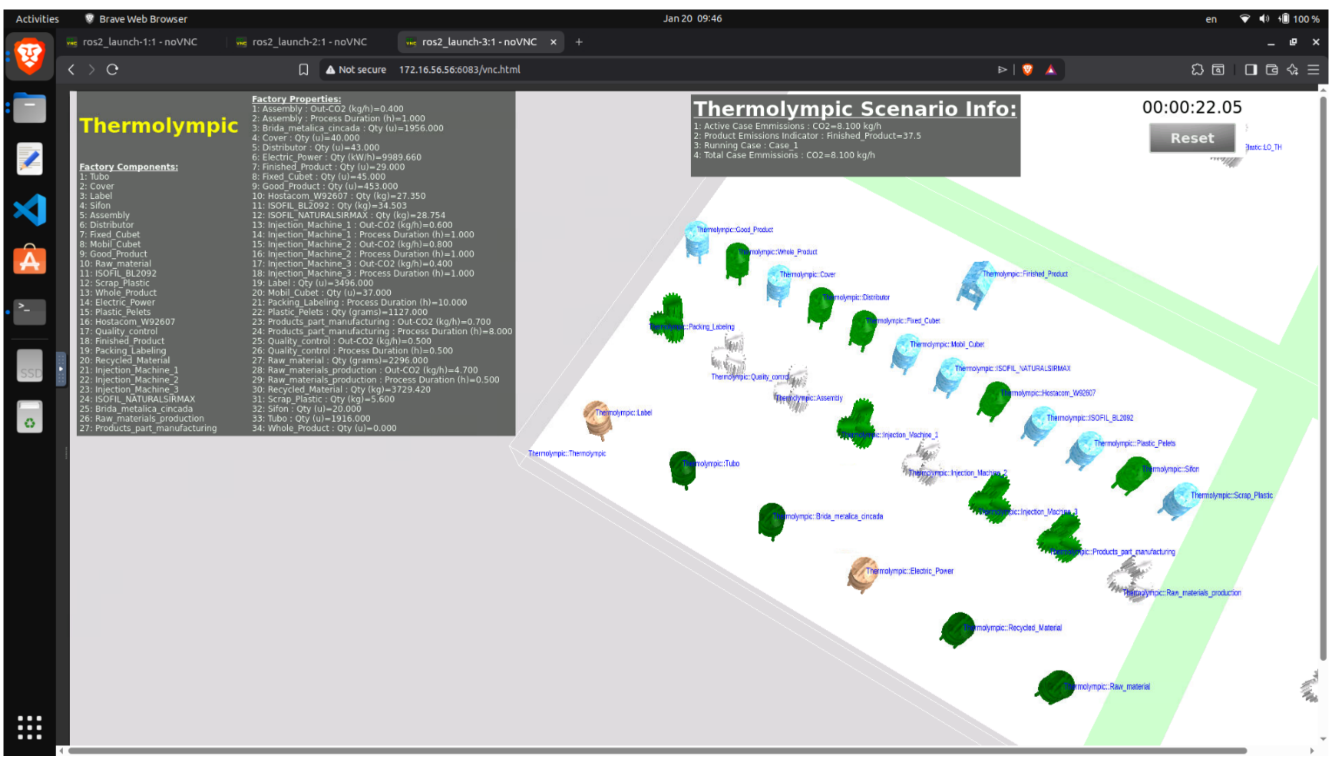

Figure 33: Factory model of Thermolympic in SCDT.

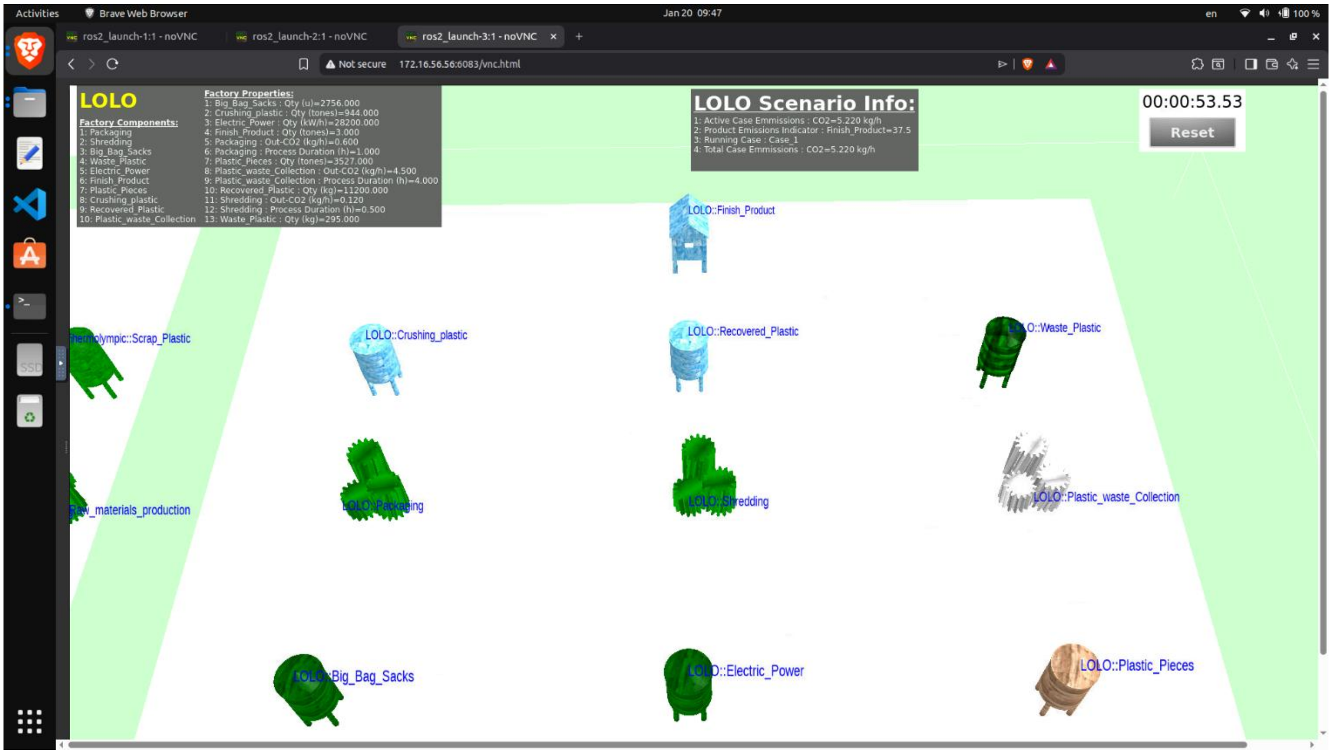

Figure 34: Factory model of LOLO in SCDT.

Supply Chain Optimization (SCOPT)

The SCOPT module is leveraged to propose alternative suppliers for the plastic pilot that provide plastic waste to the pilot in order to produce new products from recycled plastic waste, as well as to identify the interconnections between the actors in the supply chain proposed by SCOPT. An abstraction model of the supply chain motivated by the plastic pilot has been constructed to model key features of the supply chain, and the resulting model abstraction was implemented on the SCOPT tool. A scenario has been investigated utilizing four factories and two buffer zones in the supply chain, capturing the supply chain's temporary storage level. The solution provided by SCOPT in this scenario (Scenario A) proposes alternative suppliers for the plastic pilot that provide plastic waste to the pilot in order to produce new products from recycled plastic waste, as well as to identify the interconnections between the actors in the supply chain.

Additionally, this supply chain scenario has been extended, incorporating an alternative supplier for the plastic pellet to investigate how alternative suppliers can be incorporated in an existing supply chain model. The solution provided by SCOPT in this scenario (Scenario B) showcases how the proposed supply chain arrangement of the first scenario (Scenario A) is affected by incorporating a new supplier that provides additional units of plastic pellets in the supply chain to enhance the circularity of the plastic pilot. Comparing the results of Scenario B with the results of Scenario A, an important result here is that incorporating Factory A in the supply chain arrangement could increase the plastic waste. The detailed presentation of the results for the plastic pilot provided by SCOPT is described in "*D3.8 AI and Data-driven Supply Chain Optimisation M24*".

The LCA results, presented in Table 3, support the solution provided by SCOPT of incorporating an additional plastic waste supplier for the reduction of kg CO_2eq in the production of the dispenser.

3.3 Leather Pilot

In the framework of the leather pilot, the selected functional unit for the LCA is defined as the production of one bag and one keyholder. In the AS IS scenario, both products are made entirely from virgin leather, with production leftovers sent for incineration. In contrast, the TO BE scenario proposes that the keyholder is produced from the leather leftovers generated during bag manufacturing.

Two production scenarios were analyzed to evaluate potential improvements in environmental performance:

- AS IS scenario: represents the current situation, in which 100% virgin leather is used as feedstock for both the bag and the keyholder.
- TO BE scenario: represents the proposed future configuration, in which the keyholder is produced from the leather leftover obtained during bag production (cutting process).

The recycled material used in the TO BE configuration is supplied by Mototextile, the partner responsible for manufacturing the bag, while B&A is responsible for producing the keyholder from the recovered leftovers.

The overall objective of this pilot is to assess the environmental benefits of minimizing leather waste and promoting a more circular and resource-efficient production model. The analysis focuses on quantifying potential reductions in environmental impacts resulting from the substitution of virgin material with reused leather scraps.

The comparative LCA was conducted in accordance with the principles and framework established by ISO 14040 and ISO 14044. Both scenarios were modelled using OpenLCA open-source software prior to their implementation in GRETA. In OpenLCA, the LCI variables were defined based on primary data provided by project partners, complemented with secondary data from the Ecoinvent database when necessary. The models represent the material and energy flows across all relevant life cycle stages of the leather goods production process.

Once completed, both models were integrated into the GRETA platform for simulation and comparative analysis. Figure 35 illustrates the two LCA models implemented in GRETA. This integration enables a dynamic and visual assessment of environmental performance across both scenarios, facilitating interpretation and decision-making for industrial partners.

Both the AS IS and TO BE scenarios were evaluated from an environmental perspective to calculate their respective impact indicators associated with the production of one bag and one keyholder. Through GRETA, the comparative results highlight the differences between the current setup, entirely dependent on virgin leather, and the proposed configuration, which effectively avoids production leftovers.

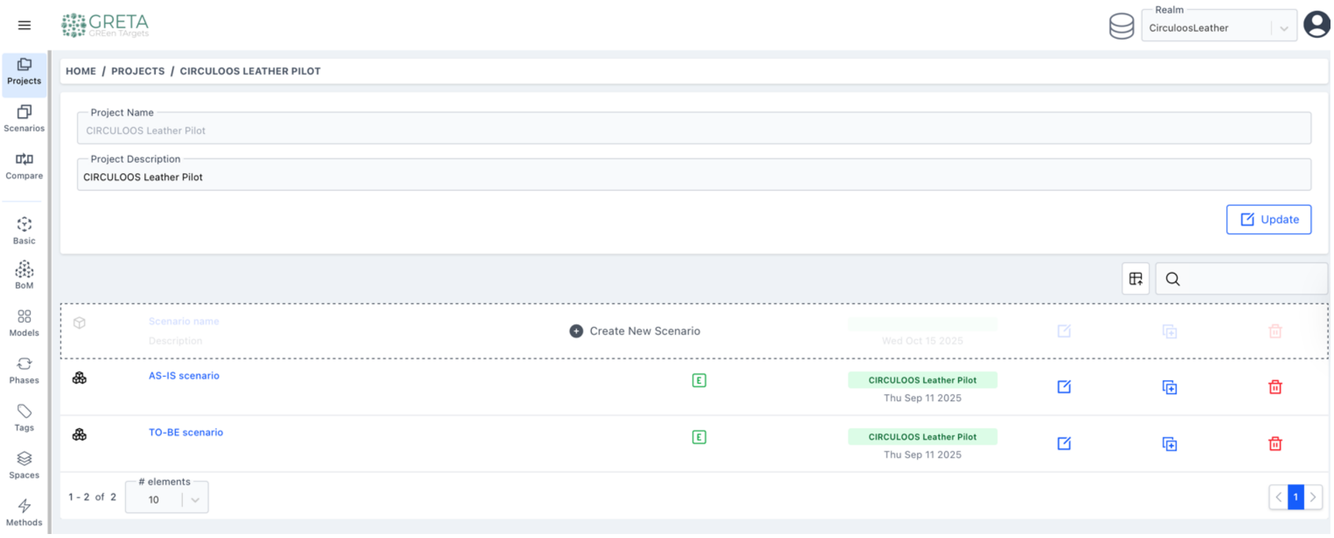

Figure 35 AS IS and TO BE scenarios for the leather pilot in GRETA

In this pilot, it is essential to clarify the approach adopted for allocation, as two processes within the system boundaries are multifunctional and therefore require allocation according to ISO 14044 principles. The first case occurs in the raw material stage, specifically in the production of rawhide, where allocation factors were applied based on literature-derived data to distribute impacts among co-products of the leather manufacturing process. The second case concerns the production of the bag and the keyholder, which are jointly modeled in the system. For this stage, an economic allocation approach was applied to distribute the environmental burdens between the two products, reflecting their relative market values. This method ensures a consistent and transparent representation of the environmental impacts associated with producing one bag and one keyholder in the TO BE scenario, where the keyholder is manufactured from the leftover material generated during bag production.

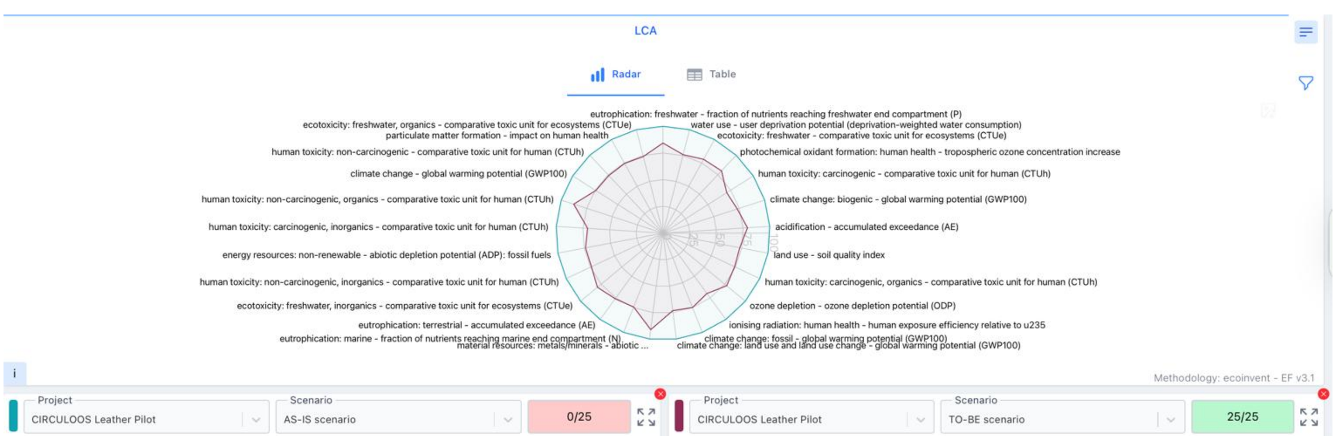

Figure 36 Comparative LCA results in Leather Pilot (generated in GRETA)

Impact Category	Unit	AS IS	TO BE	Variation (%)
Climate change – fossil (GWP100)	kg CO_2-eq	1.20×10^{2}	8.91×10^{1}	**−25.8%**
Climate change – biogenic (GWP100)	kg CO_2-eq	3.38×10^{1}	2.47×10^{1}	**−26.9%**

Climate change – land use & LUC (GWP100)	kg CO_2-eq	3.44×10^{0}	2.52×10^{0}	**−26.7%**
Acidification (AE)	mol H^{+}-eq	8.71×10^{-1}	6.90×10^{-1}	**−20.8%**
Eutrophication – freshwater	kg P-eq	3.40×10^{-2}	2.87×10^{-2}	**−15.6%**
Eutrophication – marine	kg N-eq	4.51×10^{-1}	3.36×10^{-1}	**−25.5%**
Eutrophication – terrestrial (AE)	mol N-eq	2.42×10^{0}	1.84×10^{0}	**−24.0%**
Photochemical oxidant formation (human health)	kg NMVOC-eq	3.08×10^{-1}	2.46×10^{-1}	**−20.1%**
Particulate matter formation	disease incidence	5.39×10^{-6}	4.02×10^{-6}	**−25.4%**
Ozone depletion (ODP)	kg CFC-11-eq	1.83×10^{-6}	1.41×10^{-6}	**−22.9%**
Ionising radiation (human health)	kBq U^{235}-eq	3.06×10^{1}	2.14×10^{1}	**−30.1%**
Ecotoxicity – freshwater (total)	CTUe	1.40×10^{3}	1.10×10^{3}	**−21.4%**
Ecotoxicity – freshwater, inorganics	CTUe	1.23×10^{3}	9.76×10^{2}	**−20.7%**
Ecotoxicity – freshwater, organics	CTUe	1.73×10^{2}	1.28×10^{2}	**−26.0%**
Human toxicity – carcinogenic (total)	CTUh	1.43×10^{-6}	1.01×10^{-6}	**−29.4%**
Human toxicity – carcinogenic, organics	CTUh	1.60×10^{-8}	1.18×10^{-8}	**−26.3%**
Human toxicity – carcinogenic, inorganics	CTUh	1.41×10^{-6}	9.97×10^{-7}	**−29.3%**
Human toxicity – non-carcinogenic (total)	CTUh	7.50×10^{-5}	5.55×10^{-5}	**−26.0%**
Human toxicity – non-carcinogenic, inorganics	CTUh	7.48×10^{-5}	5.53×10^{-5}	**−26.1%**
Human toxicity – non-carcinogenic, organics	CTUh	2.17×10^{-7}	1.90×10^{-7}	**−12.4%**
Material resources – metals/minerals (ADP)	kg Sb-eq	3.69×10^{-3}	3.37×10^{-3}	**−8.7%**
Energy resources – non-renewable (ADP fossil fuels)	MJ (NCV)	1.34×10^{3}	9.87×10^{2}	**−26.3%**
Water use – deprivation-weighted consumption	m^3 world-eq deprived	3.24×10^{1}	2.46×10^{1}	**−24.1%**
Land use – soil quality index	dimensionless	1.33×10^{4}	9.75×10^{3}	**−26.7%**

Table 5 Comparative LCA results in Leather Pilot (generated in GRETA)

The comparative LCA results (Figure 36 and Table 5) show a clear environmental improvement in the TO-BE scenario compared to the AS-IS configuration. Across nearly all impact categories, the use of leftovers from bag production to manufacture the keyholder reduces total environmental burdens, particularly those linked to raw material extraction. The global warming potential (GWP100) indicator decreases from 119.7 kg CO_2-eq in the AS-IS scenario to 89.1 kg CO_2-eq in the TO-BE scenario, representing a reduction of approximately 26 %. Similar downward trends are observed for other categories, such as fossil energy use (−26 %) and water consumption (−24 %), confirming that integrating leftover leather into production significantly enhances circularity and resource efficiency. The results highlight the environmental benefits of minimising waste generation and maximising material utilisation within the leather pilot.

Figure 37 shows the distribution of GWP across life cycle stages highlights the impact of material and energy flows in both scenarios. In the AS IS scenario, most emissions (~87.1%) originate from raw material production, with smaller contributions from manufacturing (~4.1%) and downstream transportation (~8.7%). In the TO BE scenario, shifting the keyholder production to use leftover leather significantly reduces raw material impacts to ~83.3% of total GWP, while the relative share of manufacturing (4.9%) and transportation (11.7%) slightly increases due to the production of new goods. This shift underscores the effectiveness of material recovery in lowering the carbon footprint of the leather pilot, primarily by avoiding emissions associated with virgin leather production.

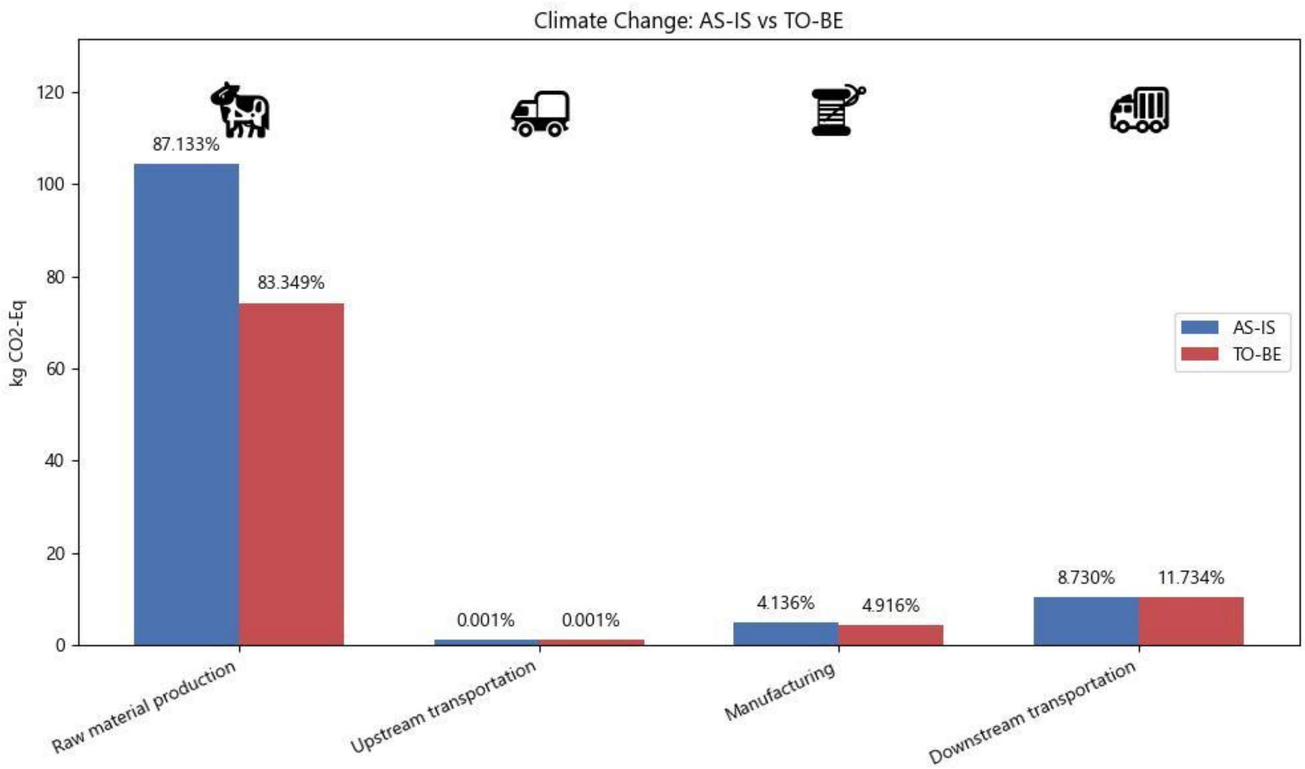

Figure 37 Distribution of GWP across Life Cycle Stages for AS-IS and TO-BE leather pilot scenarios

KPIs evaluation

The following KPIs have been defined in collaboration with the Leather Pilot partners (Mototextil and B&A) to assess the environmental and economic performance improvements achieved through the reuse of leather leftovers within the CIRCULOOS project.

Each KPI enables a direct comparison between the AS IS scenario (current production using virgin material) and the TO BE scenario (enhanced process using recovered leather scraps).

Together, they provide a holistic evaluation of emission reduction, resource efficiency, and cost competitiveness in the circular production model.

KPI Name	Description	Unit of Measurement	Partner(s)	Value	Benchmark (from DoA)
CO_2eq Emissions TO-BE (sustainability gain)	Measures the total amount of greenhouse gases emitted per functional unit, considering the entire production process (materials, energy, and logistics) for the TO-BE scenario.	%(kg CO_2-eq / FU)	Mototextil, B&A	Bag: 82.55 Keyholder: 6.47 Total: 26%	≥25%

Waste Reduction	Quantifies the percentage of solid waste avoided through the reuse of leather leftovers within the production cycle.	% (kg avoided / FU)	Mototextil	21% (30% AS IS – 9% TO BE)	N/A
Total Direct Cost Reduction	Measures the percentage decrease in total production cost per functional unit between the *AS IS* and *TO BE* scenarios. The cost includes materials, labour, energy, and other direct production expenses. It reflects the overall cost efficiency achieved with the circular production model.	%(€)	Mototextil, B&A	Bag: 0,4% Keyholder: 20%	30%
Energy saving	Energy saving due to process optimization. Avoiding frequent supply chain disruptions due to optimized supply chain arrangement, reduces the dependence on sub-optimal actors in the proposed supply chain.	€ (kWh)	Mototextil, B&A	Depending on the point of failure in the supply chain and the available alternatives. It varies between 2% (for high-availability alternatives) to >10% (for low-availability alternatives).	10%

Table 6 Leather pilot KPIs

Supply Chain Digital Twin (SCDT)

Utilizing the data provided in the SCDT templates of the leather pilot, one model per factory has been constructed in SCDT as well as the interconnections between the factories representing the supply chain arrangement of the leather pilot. The supply chain model of the leather pilot developed in SCDT is shown in Figure 38, the factory model of Mototextil is shown in Figure 39 and the factory model of B&A is shown in Figure 40. Detailed description of the SCDT implementation can be found in the deliverable D3.4 3D Digital Twin of supply chain/production/products M24.

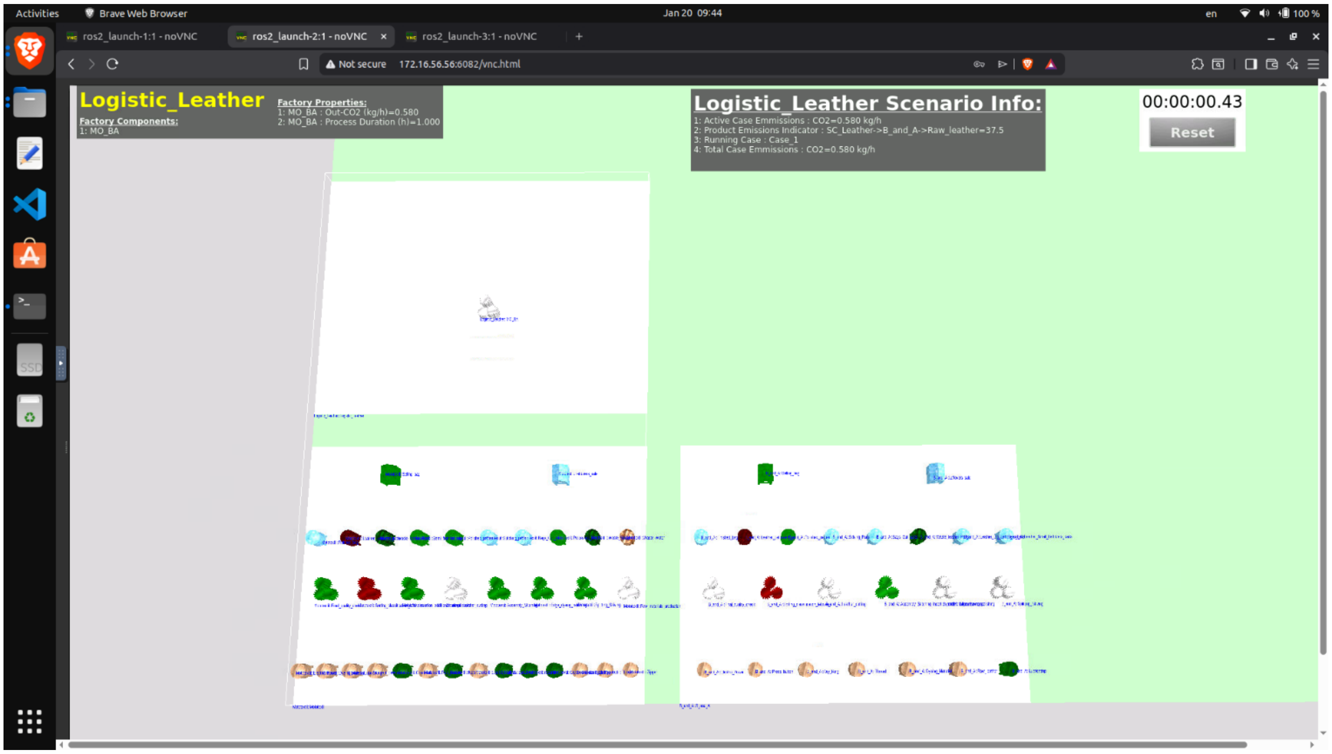

Figure 38: Supply chain model of leather pilot in SCDT.

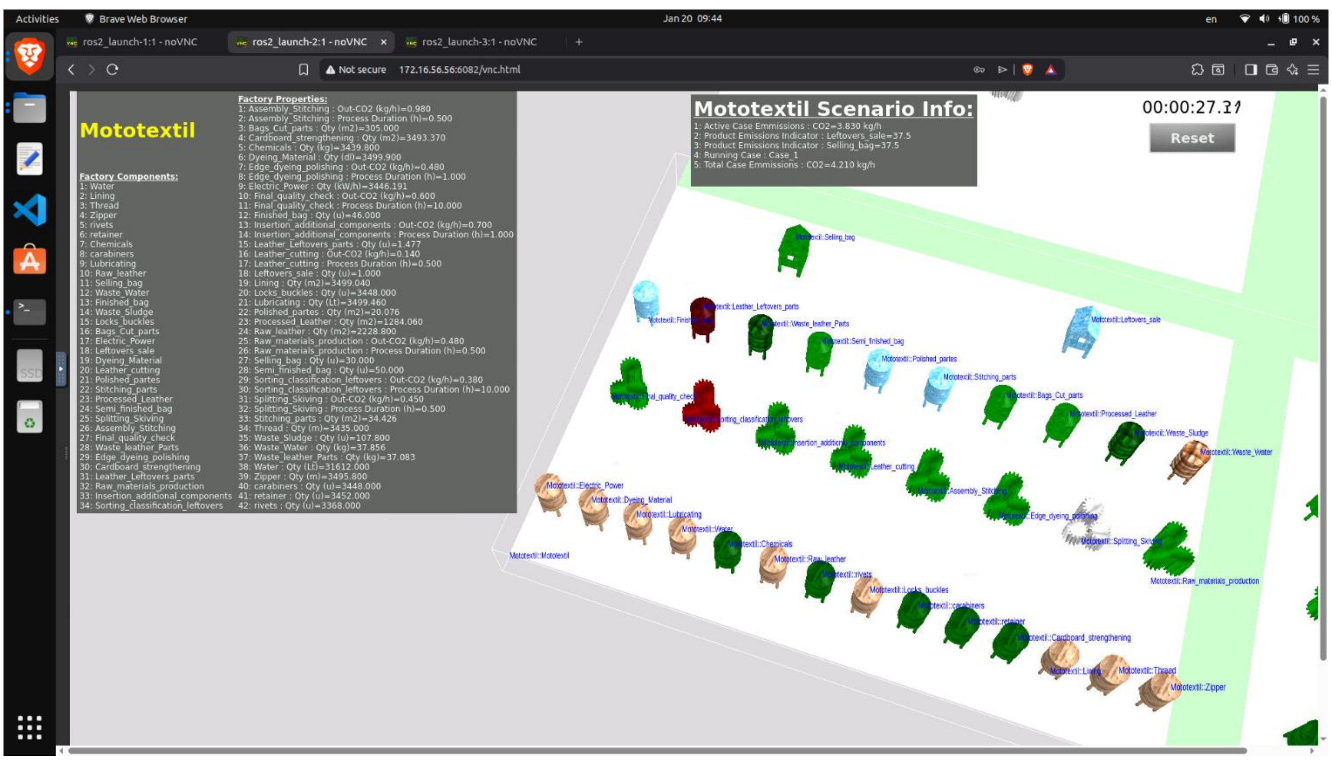

Figure 39: Factory model of Mototextil in SCDT.

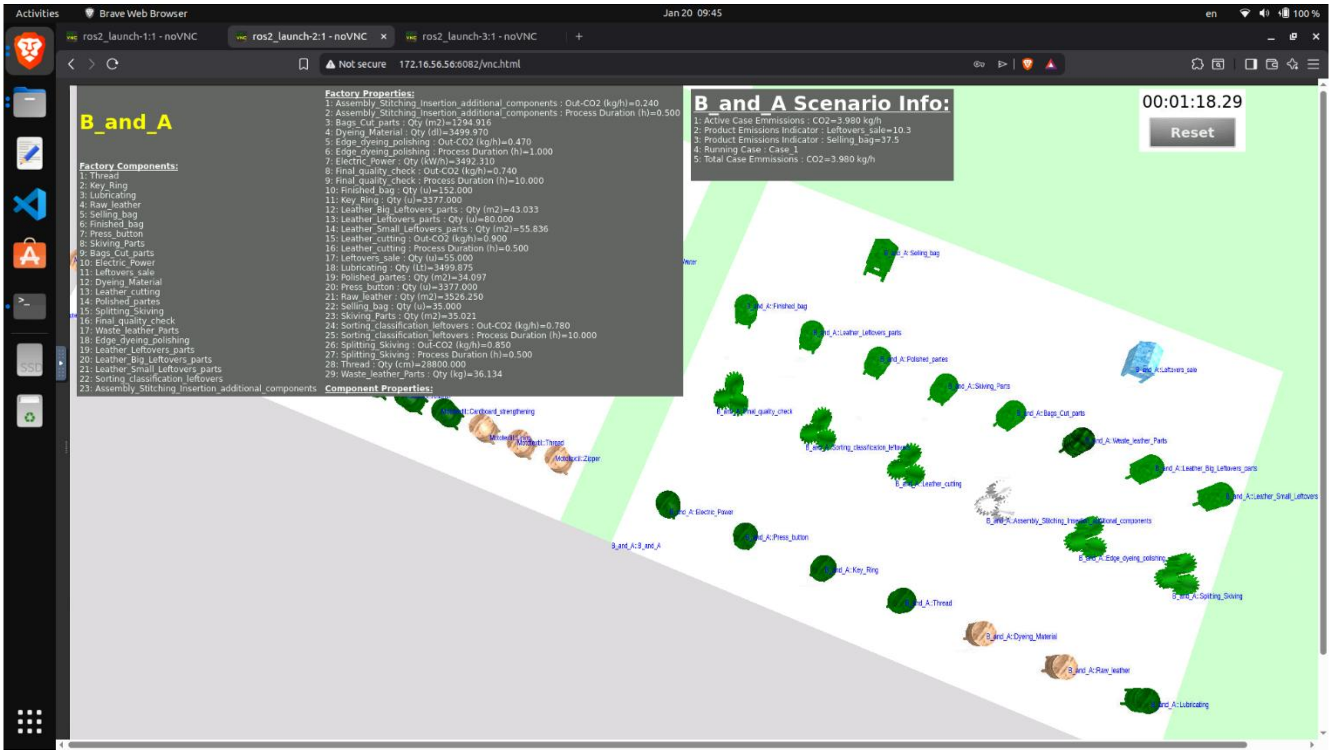

Figure 40: Factory model of B&A in SCDT.

Supply Chain Optimization (SCOPT)

The Factory visualization in the SCDT tool provides valuable information regarding particular instances of the factory workflow during the simulation. As shown in Section 3.3 in D3.4 3D Digital Twin of supply chain/production/product M24, the factory could run out of a particular input material, which will cause loss of productivity and revenues. The SCOPT tool is utilized to provide an optimal solution for supply chain stability. More specifically, SCOPT is leveraged to determine when (or whether) a factory or a process will run out of a specific material in order to prevent disruptions in the supply chain. An abstraction model of a part of the sewing process has been constructed, motivated by the leather pilot (B&A). The results provided by SCOPT in this scenario provide a scheduling plan that resolves potential disruptions in the supply chain, since the factory will run out of specific input material, which will consequently cause loss of productivity and revenues. The detailed presentation of the results for the plastic pilot provided by SCOPT is described in "*D3.8 AI and Data-driven Supply Chain Optimisation M24*".

Combining the insights provided by SCOPT and the LCA results presented in Table 5, exploiting the usage of leftovers from bag production combined with the scheduling plans for a stable supply chain of the leather pilot, ensures a smooth and efficient operation.

4 Conclusions

This deliverable presented the final implementation, execution, and evaluation of the three pilot demonstrators developed within CIRCULOOS, addressing the wood, plastic, and leather sectors across three European regions. The work consolidated the definition of the AS-IS and TO-BE scenarios, the systematic collection of Life Cycle Inventory data, the modelling of processes and supply chain configurations, and the quantitative assessment of environmental and operational performance through Life Cycle Assessment and complementary KPIs. As such, the document provides both a detailed representation of current industrial practices and a validated demonstration of how circular economy strategies can be effectively designed, implemented, and measured in real manufacturing environments.

Across all pilots, life cycle thinking enabled a transparent and robust comparison between baseline configurations and improved circular alternatives. The comparative LCA models implemented in GRETA quantified the environmental implications of each scenario and highlighted the most relevant hotspots along the value chains. Results consistently confirmed that the integration of circular practices leads to measurable and significant environmental benefits. In the wood pilot, the replacement of virgin timber with reclaimed urban wood resulted in an almost 50% reduction in Global Warming Potential per functional unit, together with reductions above 80–90% in several impact categories related to eutrophication, toxicity, and resource depletion. In the plastic pilot, the introduction of recycled granulates in four out of five components of the washing machine detergent dispenser enabled an average 25–30% decrease in climate change, acidification, and particulate matter indicators while maintaining product quality requirements. In the leather pilot, the reuse of production leftovers and the redistribution of secondary materials reduced virgin leather demand and waste generation, demonstrating clear improvements in material efficiency and circular resource use. These quantitative results confirm that even partial substitutions and targeted supply chain redesigns can generate substantial environmental gains at product level.

Importantly, the improvements observed are not solely attributable to environmental assessment itself, but to the integration of assessment within a broader digital decision-support ecosystem. The pilots demonstrate that sustainability benefits are maximised when data collection, process visibility, scenario testing, optimisation, and impact evaluation operate together in a coherent workflow. For this reason, GRETA was employed not as a standalone LCA calculator, but as the final analytical layer of an interconnected toolchain. Operational data are first structured and exchanged through the CIRCULOOS Data Platform to ensure interoperability among partners; production and logistics flows are represented through the Supply Chain Digital Twin, enabling a detailed understanding of intra- and inter-factory dynamics; alternative configurations are explored and validated through optimisation mechanisms that test feasibility and performance; and finally, GRETA quantifies the environmental and circularity impacts of each scenario, supporting evidence-based selection of the most sustainable and efficient solution.

The practical application of this approach across the three demonstrators confirms its operational value. In the wood pilot, digital modelling and optimisation supported the shift toward locally sourced reclaimed wood, reducing long-distance transport and contributing to both environmental savings and cost reductions of nearly 40–50% in raw material procurement. In the plastic pilot, simulation and assessment enabled the identification of an optimal recycled-content threshold compatible with technical constraints, ensuring both environmental improvements and stable production quality. In the leather pilot, improved visibility of leftover availability facilitated internal reuse and cross-company exchanges, reducing waste and increasing the valorisation of secondary materials.

Overall, the three pilot demonstrators confirm that coordinated digital orchestration and sustainability intelligence can deliver tangible, measurable benefits, including double-digit reductions in greenhouse gas emissions, significant decreases in resource consumption, improved material circularity, and enhanced operational efficiency. The results validate both the technical feasibility of the proposed solutions and the strategic vision underpinning the project: enabling MSMEs to design, simulate, optimise, and assess circular supply chains through integrated digital support. The experience gathered provides a solid and replicable foundation for future experiments and open calls, demonstrating that the transition toward circular manufacturing can be systematically supported through data-driven tools and evidence-based decision-making, thereby accelerating the adoption of resilient, resource-efficient, and sustainable business models across European manufacturing ecosystems.

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