Product Passport through Twinning of Circular Value Chains

Deliverable 4.2

Report on piloting activities

WP4: Circular Process Industries Demonstration

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Author	Aris Zompras (ACCELI)
Contributor(s)	Nikolas Kellas (ACCELI), Stavros Lounis (AUEB), Andreas Katsigiannis (KPAD), Tryfon Kekkes (ASPIS), Jose Gonzalez Castro (EUT), Barbara Fernandez (BARNA), Ana Seoane (IMA), Linda Leonardi (CETMA), Silvio Pappada (CC), Vincenzo Castorani (HPC), Nikolaos Sifakis (TUC), Kostas Kalaboukas (MAG)
Reviewer(s)	Margherita Forcolin (MAG), Maria Aryblia (TUC)
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Executive Summary

This report outlines the outcomes of the initial piloting activities carried out as part of the Plooto project. The project's primary goal is to demonstrate the viability of circular economy practices in various industrial sectors, with a focus on transforming waste materials into valuable products. This effort aims to reduce environmental impacts while promoting resource efficiency. Three pilots were implemented, each targeting a different waste stream: the reuse of Carbon Fiber Reinforced Polymer (CFRP) waste for drone manufacturing, the recovery of magnets from Waste Electrical and Electronic Equipment (WEEE), and the valorisation of citrus processing waste into juice by-products.

In the CFRP waste pilot, the transformation of uncured prepreg scraps into components for Unmanned Aerial Vehicles (UAVs) showcased how requalifying waste materials can yield both economic and environmental benefits. The WEEE pilot concentrated on recovering magnets from discarded electronics and integrating digital traceability to optimize the recycling process. Meanwhile, the citrus waste pilot explored how molasses and essential oils can be produced from by-products of citrus processing, highlighting the potential for reducing energy consumption and environmental footprints in food industries.

A key enabler in all pilots was the Plooto platform, which provided digital tools for tracking material flows, ensuring traceability, and optimizing production. This platform facilitated collaboration between partners, increasing transparency throughout the supply chain.

The results thus far show substantial reductions in waste, shorter production cycles, and the creation of new revenue streams from secondary raw materials. The pilots underscore the importance of digitalization, cross-sector collaboration, and adaptability in successfully implementing circular economy models. Moving forward, the next phase will involve refining these processes, expanding the pilot activities, and exploring how the results can be replicated across other sectors and regions.

The second iteration of the pilots will aim to build on these successes, with findings from this phase captured in an updated report. This will provide further insights into how waste reduction, resource efficiency, and sustainable practices can be advanced in manufacturing and processing industries.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

Acronym	Description
CDT	Cognitive Digital Twin
CFRP	Carbon Fiber Reinforced Polymer
CNC	Computer Numerical Control
CPW	Citrus Peel Waste
CPWW	Citrus Peel Waste Water
DPP	Digital Product Passport
EO	Essential Oils
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
PM	Permanent Magnet
PSM	Process Simulation and Modelling
SBSC	Sustainability Balanced Scorecard
SME	Small and Medium-sized Enterprise
SRM	Secondary Raw Material
UAV	Unmanned Aerial Vehicle
WEEE	Waste from Electrical and Electronic Equipment
WP	Work Package

1 Introduction

1.1 Purpose of the Deliverable

The purpose of this deliverable is to provide a comprehensive overview of the piloting activities carried out as part of the Plooto project, focusing on the practical application of circular economy principles within selected industrial sectors. This deliverable captures the detailed implementation and results of pilot projects aimed at demonstrating the feasibility and benefits of reusing waste materials, such as Carbon Fiber Reinforced Polymers (CFRP) and Waste Electrical and Electronic Equipment (WEEE), to produce new high-value products like drones and magnets.

The pilot reports are integral to the overall project as they serve as practical case studies that validate the project's core objectives, such as resource efficiency, sustainability, and circularity. By systematically tracking and evaluating the performance of each pilot, this deliverable ensures that the lessons learned, challenges faced, and results achieved contribute to refining the Plooto platform and informing future initiatives.

This deliverable is particularly valuable to both the consortium and external stakeholders, as it offers insights into the technical feasibility, economic benefits, and environmental impacts of adopting circular economy practices in different industrial contexts. For the consortium, it serves as a critical feedback mechanism for continuous improvement, while external stakeholders, including industry professionals and policymakers, can use the findings to explore the replicability and scalability of these innovations in their own sectors.

A second version of this deliverable will be prepared following the second iteration, which will include detailed KPIs and comprehensive feedback on the tools and services provided by the Plooto platform from a user perspective. This future version will enrich the analysis by capturing quantitative metrics and user-driven insights, providing a more robust evaluation of the platform's functionality, usability, and impact on circular economy practices across industries.

1.2 Relation with other deliverables

This deliverable relates to other deliverables in various aspects, as it describes the practical application of the methodological approach for impact assessment, developed in D4.1, in the context of the pilot activities. Furthermore, it is linked with D1.1 “Plooto methodological approach and business cases specifications v1”, as it builds upon the methodological approach and business case specifications described therein. Moreover, there is a direct link with D2.3 “Plooto complete suite of services v1”, D3.1 “Product passport and certification tool v1”, D3.5 “Plooto balanced scorecard v1” and D3.3 “CRIS integrated platform v1” as they provide the specifications and the technological aspects of the Plooto platform and services. Finally, D4.3 will serve as the follow-up to D4.2, capturing further iterations and refinements of the pilot activities, drawing from the initial results presented in this deliverable. The results of the pilot projects assessment will be presented in D4.4.

1.3 Structure of the Document

The structure of the deliverable is designed to guide readers through the piloting activities and their outcomes in a clear and organized manner. The document is divided into several key chapters, each focusing on specific aspects of the pilots, from their objectives to the detailed results and lessons learned. Therefore, the document is structured as follows:

- **Sections 2-4** describes in detail each pilot's activities, covering the goals, operations, results, and key performance metrics. Pilot 1 explores citrus processing waste for juice by-products, Pilot 2 covers WEEE for magnets, and Pilot 3 addresses CFRP waste for drone manufacturing.
- **Section 5** summarizes the overall findings of the piloting activities and provides recommendations for further development and replication of the project's outcomes. It also suggests directions for future pilot implementations and scalability.

1.4 Pilot Reporting Framework

The Pilot Reporting Framework outlines the standardized approach for collecting, analysing, and presenting data across all pilot activities. The framework leverages the *5W1H* methodology, as established in D4.1, ensuring that each pilot is systematically evaluated based on predefined Key Performance Indicators (KPIs). These KPIs are tailored to reflect the unique contexts and goals of each pilot, enabling both quantitative and qualitative assessments. The framework supports the two-round evaluation process outlined in D4.1, where pilot performance is first assessed to identify initial improvements (M19-M22) and later reevaluated for final validation (M31-M36). Data collection will be based on real-time monitoring through the Plooto platform, supplemented by structured interviews and feedback from stakeholders. This ensures a comprehensive understanding of pilot impacts, covering areas like system functionality, usability, and sustainability performance. The reporting framework also includes a comparative analysis across pilots to identify cross-pilot challenges, best practices, and areas for potential scalability and replication.

2 Pilot 1: CITRUS PROCESSING WASTE FOR JUICE BY-PRODUCTS

2.1 Pilot description

Aspis is a Greek citrus-processing plant producing a great variety of fruit juices and purees, aromas and oils, fruit preparations and canned products. It has processing plants in two different regions in Greece. The first one is located in Argos, where they process citrus and deciduous fruits and vegetables, producing juice and purees, citrus oils and aromas, fruit preparations and mixtures. Moreover, the company also produces animal food from citrus peel. The second processing plant is located in Irinoupoli, where they process deciduous fruits and vegetables, producing juice and purees, aromas, fruit preparations and mixtures. In Irinoupoli, they also produce private label fruit and vegetable juice in TetraPak® packaging as well as fruit halves, slices or dices in cans or aseptic drums.

During the industrial production processes, various by-products are generated, like:

- Citrus pellets from orange peel of citrus waste that have the same characteristics as the original plant residues (oil and water content).
- Citrus peel oil that contains up to 95% d-Limonene and stripper oil, recovered during the liquor stage.
- Citrus molasses during the press liquor and stripper oil. Molasses is a by-product of citrus juice extraction, which is sold to distilleries or reincorporated in dried citrus pulp.

The Greek pilot focuses on utilizing various waste streams, especially on citrus molasses, produced during citrus processing. This initiative aims to demonstrate the feasibility and benefits of producing citrus molasses, with reduced environmental impact and promote them to the markets, giving a strategic advantage to the pilot. The processing line of the plant, as constructed in the process simulation modelling tool provided by TUC, which is presented in Figure 11.

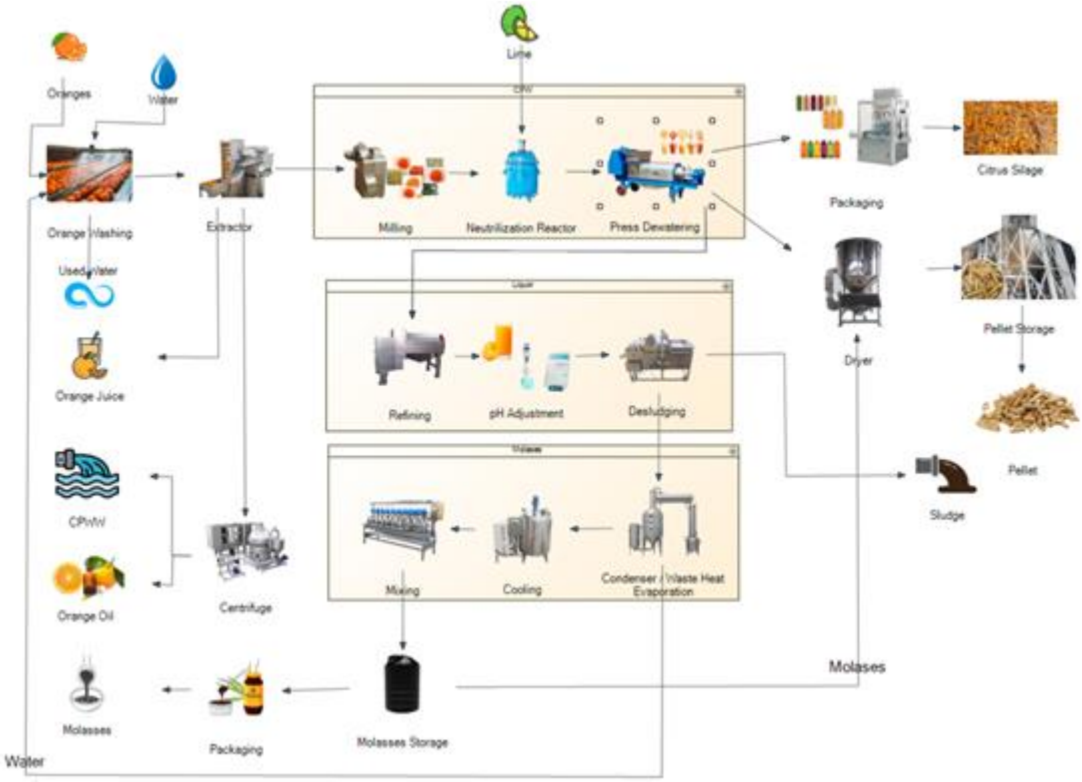

Figure 1: Process Simulation & Modelling of the production process of the Greek pilot

2.2 Objectives and expected outcomes

The main objective of Plooto is to deliver a digital transformation framework that will foster a wider adoption of circular practices in manufacturing, with the overarching goal to maximize energy reduction through Plooto platform, utilizing analytics tools from FRONT for detection of anomalies in production, and promote more sustainable products that will be characterized by a Life Cycle Assessment (LCA) from KPAD and will bear a Digital Product Passport (DPP) and a Sustainability Balanced Scorecard (SBSC), provided by MAG and TUC respectively. All necessary information is distributed through Cognitive Digital Twining from Plooto (Figure 2).

To that end, through Plooto the pilot aims to valorise citrus peel waste (CPW) and citrus peel waste water (CPWW) to produce Essential Oils (EO), Molasses and animal feed. Currently, the main focus is on condensation of Molasses and centrifugation of water/oil slurry. Additionally, through the development of Cognitive Digital Twins (CDT) from Plooto, the pilot will evaluate the recovery of the aforementioned valuable byproducts, using the predictive and prescriptive analytics tools that Plooto provides. Finally, the new products will include a DPP and will be evaluated by LCA, SBSC's Circularity Index and the Product Configuration & Performance Monitoring from Plooto platform.

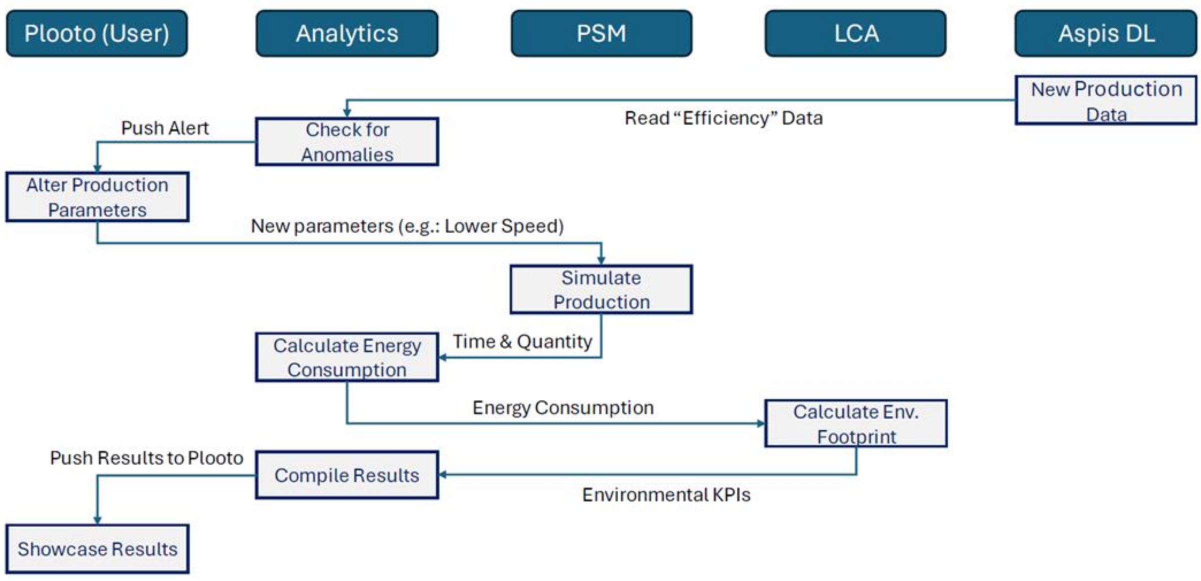

Figure 2: Plooto interactions for ASPIS in case of anomaly triggered by the new Data Lake

The outcome of the Plooto collaboration will be reflected in the aims, KPIs and assessments for the pilot, which are shown in table below.

Table 1: KPIs aims, expectations and current status

KPI	As is	To be	Current value
Production of animal feed	10000-15000 tn	At least 20000 tn after project lifetime	15000tn
Production of high-quality molasses	2000-2000 tn	3000-3500 tn after project lifetime	2000tn
Production of d-Limonene	0.5-1.5 tn	At least 2 tn withing project lifetime	1.0tn
Volume of CPWW	150000-250000 tn	At least 10% decrease	200.000tn
COD of CPWW	10000	At most 2000	10.000
Volume of CPWW that goes to biological treatment	100% (after 1+ cycle)	At least 40% decrease	100%
Revenues from animal feed	1 million (€)	2 million (€)	0.7 million (€)

2.3 Pilot Operations

The first iteration of the Greek pilot focused on validating the functionality of the Plooto platform and its effectiveness in real-world conditions, particularly regarding the production of citrus molasses. These streams include steps that are prone to anomalies, resulting in high energy demands, thus leading to significant environmental footprints. In this iteration Plooto utilizes analytics for the molasses stream to detect incoming anomalies and perform life cycle analysis to estimate the resulting environmental burdens. Additionally, through the SBSC the resulting citrus molasses will be characterized for their performance on waste reusability and resulting capital growth, while a digital product passport will help to promote them to new markets and end users, providing a competitive advantage both at local and national levels.

2.4 Results and KPIs achieved

2.4.1 Process Simulation & Modelling tool

The Greek pilot aims to demonstrate the feasibility and benefits of converting citrus waste, which is typically discarded, into high-value products such as molasses and essential oils. This pilot highlights the importance of end-to-end traceability and quality assurance in the production of juice by-products from citrus waste. Through data integration provided by the Process Simulation & Modelling (PSM) tool, the pilot ensures that the conversion process will be accurately modelled. The Greek pilot serves as a model for other similar industries looking to adopt circular economy practices, demonstrating the economic and environmental advantages of repurposing fruit-juice waste into valuable resources.

The production line of the Greek pilot is shown in Figure 1 above and described in D2.3. Briefly, the processing value chain begins with the orange washing process, and moves on to the extraction, where two primary streams are produced: orange juice and citrus peels (CPW). Orange juice is further processed to produce clarified orange juice, the main end product, while CPW undergoes milling and neutralization through various acids and bases to make them suitable for further use. The neutralized CPW are then dewatered using press dewatering, which produces two output streams: dewatered CPW and press liquor. The press liquor then undergoes pH adjustment and desludging to remove any remaining solids, resulting in a clarified liquid. Finally, the clarified liquid undergoes evaporation and condensation to result in the desired citrus molasses, which are then packaged and stored for distribution.

The PSM tool significantly contributes to the Greek pilot by providing a comprehensive platform for modelling, simulating, and optimizing the entire value chain of citrus waste processing. The PSM tool facilitates real-time data integration, allowing for dynamic updates and adjustments to process models based on actual operational data. This ensures that the simulations accurately reflect the real-world conditions and enable effective decision-making, particularly in case of anomalies. The tool also supports detailed "what-if" scenario analyses, helping to identify optimal conditions and process parameters that maximize efficiency and yield.

2.4.2 Digital Twinning

The DT process models focus specifically on automated features and aspects that need to be monitored. To that end, some steps defined in the PSM have been aggregated in the DT process models. Four types of assets have been identified (Material, Machinery, Activity and Process) and the relevant telemetries have been established for each asset.

The Greek pilot focuses on internal production of Aspis partner; no collaboration with external parties is foreseen. The interesting aspect of the pilot is the use of CPW from the production of the main products (juice/fruit purée) to produce citrus molasses; thus, opening potential future scenarios for a more sustainable production. However, the production of citrus molasses involves steps that are energy intensive and depend on several parameters that need to be monitored and controlled, in order to result in a sustainable production. The main DT processing steps have been identified and current focus is on the Liquor treatment step.

2.4.3 Life Cycle Analysis

The LCA of the baseline scenario of the Greek pilot has been completed from KPAD, according to ISO 14040 standard and ReCiPe 2016 methodology [1][2]. Some indicative results are presented in Table 2. Notably, the results of the LCA study will be used in the online LCA tool, developed by Frontier Innovations and KPAD, which will provide the environmental data for the analytics, SBCS and DPP services of Plooto.

Table 2: Results from LCA of the Greek pilot

Studied parameter	Value
Climate change, excl. biogenic carbon [kg CO2 eq.]	10400
Fossil depletion [kg oil eq.]	3270
Freshwater consumption [m^3]	2070
Fine Particulate Matter Formation [kg PM2.5 eq.]	14
Human toxicity, cancer [kg 1,4-DB eq.]	5.92
Metal depletion [kg Cu eq.]	98.30

The online LCA tool will be used to assess the environmental impacts in case of anomalies and "what-if" scenarios and compare results with the provided baseline.

2.4.4 Analytics

For the Greek pilot, the required information has been gathered and analysed. For every step, the corresponding measurements have been collected and their descriptions have been documented and published in D2.3. Briefly, the first iteration of the analytics component of Plooto is focused on the desludging step of the Greek pilot, due to the significantly high energy demands and resulting environmental footprints. Several key factors have been identified that can potentially lead to high energy consumption.

The approach is focused on the extraction of meaningful insights regarding unusual energy consumption. By combining the three variables (soluble solids, insoluble solids, pH) that are measurements inside the decanter step of the process and complementing them when needed with predicted and simulated data, the overall efficiency is increased and the high energy consumption is significantly reduced. Additionally, in case of out-of-range values, the tool will warn Plooto users of a potential anomaly that can cause significant increase of the required energy and thus allow for mitigating measures.

As described in D2.3, the tool achieves this by including three distinct parts: Forecasting (combined with Convolutional Neural Networks and LSTM [3]), Environmental (using online LCA tool) and Anomaly Detection & Recommendation part (implementing Z-score and heuristic methods [4][5]). In case of an anomaly and based on the corresponding functional requirements of the Greek pilot, a system composed of several interconnected components has been designed and implemented, specifically designed to cover data extraction and transformation needs[1] [2], covered in detail in D2.3.

The analytics tool is integrated with Plooto main platform using an API endpoint and the data sources are defined following a specific, compatible data schema (Figure 3).

Figure 3: Integration with Plooto main platform

2.4.5 Sustainability Balanced Scorecard

The Sustainability Balanced Scorecard (SBSC) utility in the Plooto project focuses on the assessment of sustainability and circularity across the value chain based on the objectives and preferences of each Plooto use case. For this purpose, the Greek pilot has provided the necessary information about the KPIs that is willing to include in its SBSC regarding environment, society, governance, and economy & growth. Since the Sustainability Balanced Scorecard for the Greek pilot is ongoing under WP3, the results and the overall assessment will be available at the next and final version of this report. Nevertheless, SBSC of the Greek pilot will empower the industry at both local and national levels by providing a competitive advantage [6][7][8]. This advantage stems from offering open access to sustainability information to all relevant actors, stakeholders, collaborators and customers.

2.4.6 Digital Product Passport

As described in the D3.1, the Digital Product Passport (DPP) aligns with the Eco-design Directive 2009/125/EC and is designed to provide information in a way that is easily accessible, in order to help consumers and businesses to make informed choices when purchasing products, to facilitate repairs and recycling and to improve transparency about products' environmental footprints on a lifecycle basis. Additionally, it enables digital registration, processing and sharing

[1] https://flask.palletsprojects.com
[2] https://superset.apache.org/

of product-related information amongst supply chain businesses, authorities and consumers[3] [4] [5] [6]. A DPP can facilitate consumer and businesses to make informed choices. The current design for the DPP of the produced molasses from ASPIS includes four categories: Product description, Nutritional analysis, Specifications and Environmental impact. The information provided by DPP will be accessible through a QR code that will be placed in the product packaging bag. When scanned, it will redirect the consumer to the DPP website.

2.4.6.1 Current status

The DPP of the Greek pilot is integrated and accessible from the Plooto platform (Figure 4, Figure 5 and Figure 6).

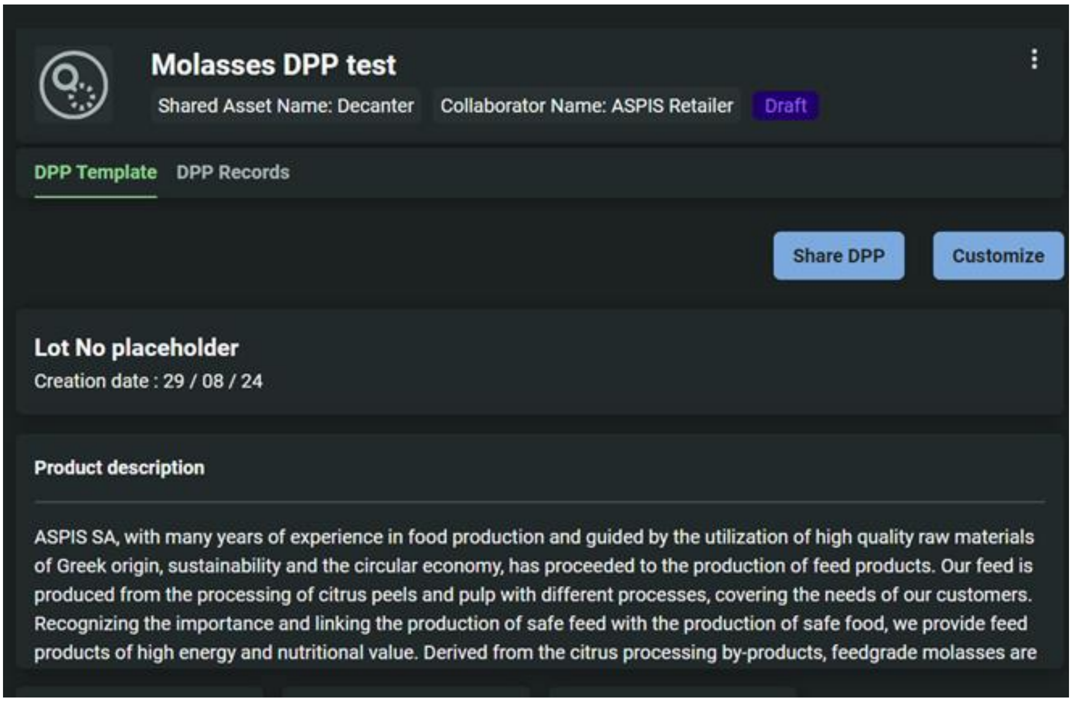

Figure 44: Product description of Molasses DDP in Plooto

[3] https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2022/0095(COD)&l=en
[4] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13682-New-product-priorities-for-Ecodesign-for-Sustainable-Products_en
[5] https://www.europarl.europa.eu/RegData/docs_autres_institutions/commission_europeenne/com/2022/0142/COM_COM(2022)0142_EN.pdf
[6] https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en

Figure 5: Nutritional analysis and specifications of Molasses DPP in Plooto

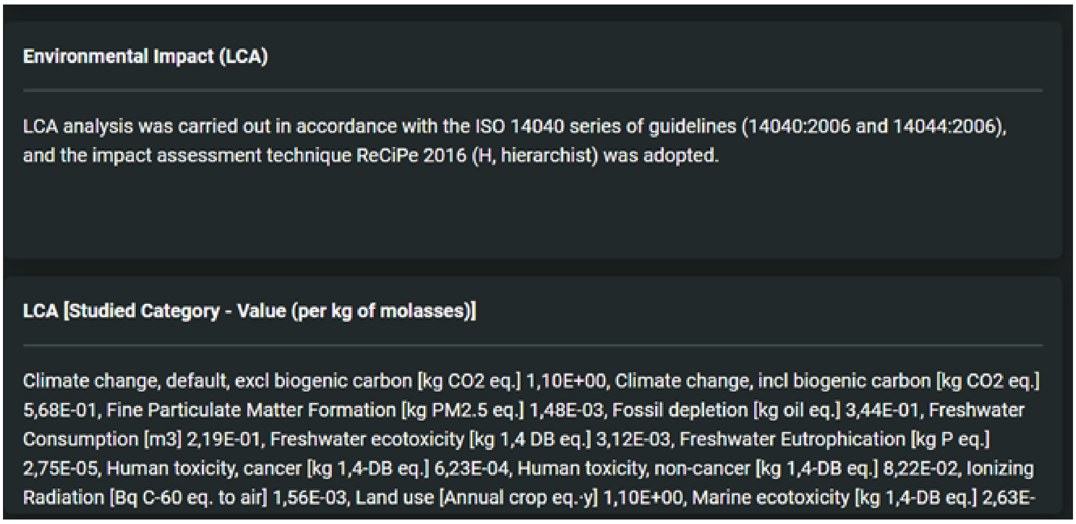

Figure 6: Environmental impact (LCA) of Molasses DPP in Plooto

2.5 Lessons learned and challenges

There are still some challenges for the Greek pilot to achieve its aims towards the increase of the valorisation of the waste streams for the production of value-added byproducts. Firstly, the input stream is assumed of the same quality and type. As such, the main challenge is the availability of raw materials and the impact of climate change on the future crops.

Regarding the processing stage, the variability of the material condition (e.g., silane, initial and final humidity etc.) and brix concentration affects the production of the wastewater, which needs to be cleaner wastewater with reduced COD that will allow processing in a biological wastewater treatment and reuse of the treated stream, effectively reducing the volume of the produced byproducts. This shall promote sustainability & environmental safety and also ensure compliance with Directives 98/83/EC and 2015/75/EU of the European Union for environmentally friendly disposal of wastewater and solid wastes. Additionally, the reduction of the overall energy demands with precise process adjustments is a particular challenge, especially nowadays with the rising energy costs, as there are a lot of production requirements regarding the safety and quality of the end products that need to be fulfilled. The initial analysis from analytics suggested focus on the liquor step and the current implementation is expected to contribute significantly to the plant's overall energy demands.

Additionally, market competition creates additional pressure to the company regarding changes towards sustainability, nevertheless, it is expected that the innovations in Plooto will bring the company a step ahead, provided that a proper marketing and communication strategy will be implemented.

3 Pilot 2: WEEE FOR MAGNETS

3.1 Pilot Description

The Spanish pilot is focused on recycling magnets from Waste Electrical and Electronic Equipment (WEEE). The pilot members involve a recycling company (Ferimet), a research lab specialized in magnets processing (IMDEA) and a bonded magnets manufacturer (IMA). In addition, Eurecat coordinates the pilot and is supporting Ferimet by designing a robotic system that could help in the dismantling process.

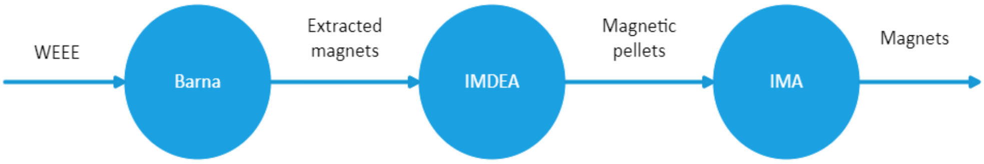

Figure 7: Magnet Recycling Process Flow

Ferimet, the largest recoverer of ferrous and non-ferrous materials in Spain, extracts magnets from different WEEE received at their plant in Granollers, nearby Barcelona. The extracted magnets are sent to IMDEA, a material research centre in Madrid hosting the group of permanent magnets and applications. With their expertise in magnet processing, they process the extracted magnets to obtain magnetic pellets that can be used to manufacture new magnets. These pellets are sent to IMA which manufactures precision magnets following their clients' specifications.

3.2 Objectives and Expected Outcomes

The WEEE recycling pilot has two main objectives. The first is to set up the magnet recycling process and initiate collaboration between key partners in recycling and magnet manufacturing. Then, the CDT will monitor the production and ensure the economic feasibility of the supply chain. This will be achieved through the inclusion of different tools that will aid the pilot partners in improving their operations and assure transparency with the implementation of the DPP services.

The expected outcomes include:

- **Reduction of WEEE landfilled**: The magnets extraction from WEEE will contribute to reduce the total waste produced and will increment the circularity processes in the UE.
- **Use secondary raw materials in permanent magnets (PM) manufactured from pellets**: The objective is to increment the usage of recycled pellets in the manufacturing of bonded permanent magnets.
- **Validate the recycling process for different materials**: PMs are manufactured from various materials. The aim is to recycle magnets made of bonded NdFeB and Sr-Ferrite either bonded or sintered.
- **Minimise the insertion of non-recycled raw magnetic material**: To achieve the required magnetic properties, it might be necessary to add raw magnetic material to the pellets. The aim is to minimize the use of raw material.

3.3 Operations at Pilot Sites

The first iteration of the WEEE pilot has focused on developing and implementing the different digital solutions for the Ferimet and IMDEA use cases. Thus, the IMA functionalities will serve as a replication case of the digital solutions previously developed.

Also, all pilot companies have worked to set up the supply chain. For that, they have prepared different tests to ensure the feasibility of the proposed supply chain and assure the recyclability of the recovered magnets.

3.3.1 EUT

The robotics department has more than 15 years of experience, developing innovative solutions in three main areas: robotic manipulation, mobile robotics and cognitive systems. The department has participated in projects in various sectors, including industry, agriculture, construction, mobility, even food, always focused on providing robots with dexterous manipulation capabilities to improve productivity and quality using advanced technologies such as learning by demonstration, learning by reinforcement and generative AI.

In the field of "Waste from Electrical and Electronic Equipment", the department has designed specialised robotic solutions for the disassembly of devices such as electric vehicle batteries and domestic appliances, among others. These technologies enable automated component removal, optimising resource recovery, minimising human exposure to hazardous materials and providing real-time reporting on the efficiency and environmental impact of the process.

During this stage of the project research has been carried out into existing robotic solutions for magnet recovery, considering the different technologies used in this type of operation. It has also been studied how robots can be used in the process of dismantling electrical devices, allowing faster and more efficient access to the magnets. During this study, robots have been identified to assist in component handling and unscrewing tasks. These activities, which require constant precision and can become repetitive and tiring for human operators, are ideal for robotic automation, as robots offer greater precision and can perform these tasks continuously without the risk of errors due to fatigue. These applications can also be used for any other electronic device: once the robot learns the task of unscrewing, it can apply this task to any screw, regardless of the device it is in. In addition, with the help of machine vision systems and AI algorithms, the robot can identify different elements and their positions, allowing it to automatically adjust in real time to the different tasks and positions required.

The next step consisted of preparing the design of a robotic cell in simulation, incorporating all the elements necessary to evaluate the operations to be carried out by the robot. With this simulation it is possible to check whether the workspace is adequate, and that the robot can perform the tasks without problems, avoiding collisions with other objects or risks to the safety of the operators. The simulation ensures that the robot can operate efficiently and safely, ensuring that the interactions between the robot and the humans in the cell do not compromise the accuracy and productivity of the system.

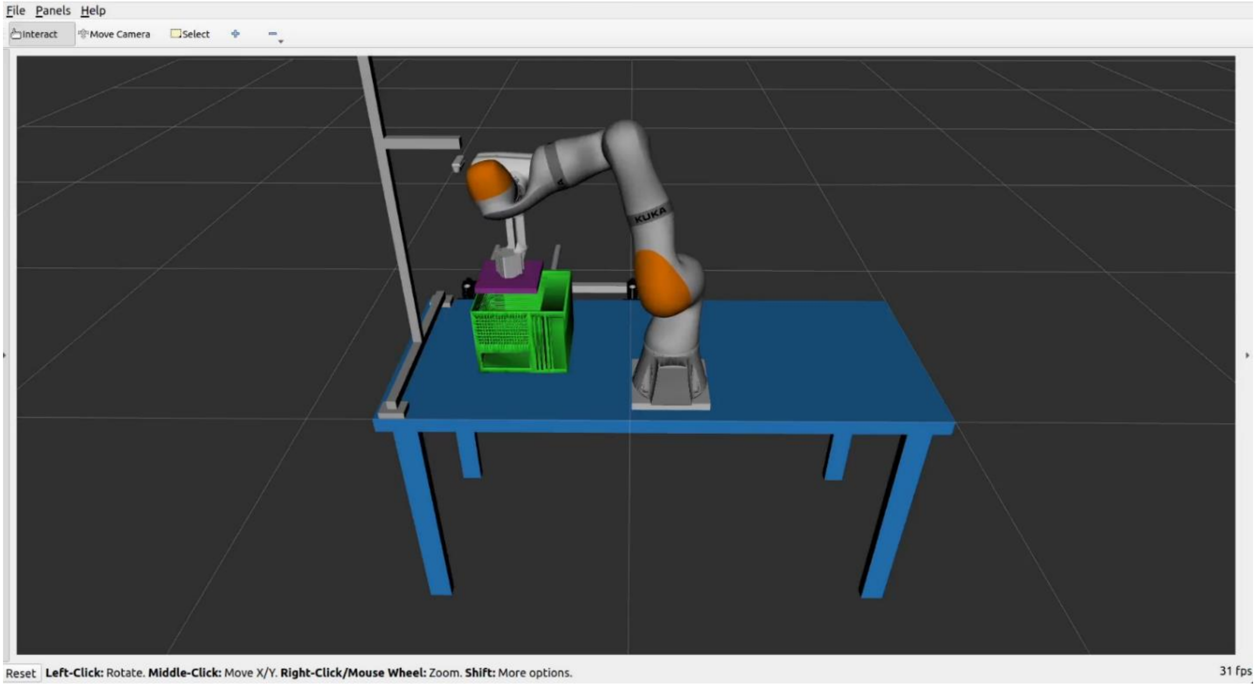

Figure 8: Simulated Robotic Cell for Component Handling

Once the station had been validated in simulation, the next step was to mount a machine vision camera on the robot for the component identification stage. For the vision system to work properly together with the robot, both intrinsic and extrinsic calibration of the camera was necessary. Intrinsic calibration adjusts the camera's internal parameters, such as lens distortion and focus, ensuring that the captured images are accurate. Extrinsic calibration, on the other hand, sets the position and orientation of the camera in relation to the robot, allowing the two to work in a coordinated manner. This process ensures that the robot can correctly interpret what the camera is seeing, adjusting its movement accordingly to operate accurately.

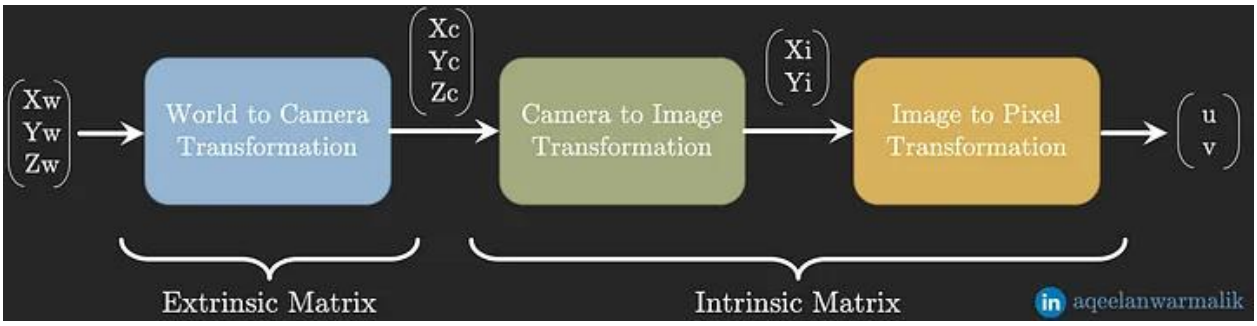

Figure 9: Calibrating the Robot's Vision System: Intrinsic and Extrinsic Parameter Adjustment

Finally, we have created a dataset to train the machine vision system, which includes images and data of the different components that can be found in a PC tower. Given that it has not been possible to access the electrical devices in the project to recover the magnets, it has been decided to study their recovery in other electronic devices, specifically computer hard disks. This dataset has allowed the system to learn to accurately identify each component, from screws to boards. At the end of these steps, the robotic system is ready to start working with the behavioural robotics application.

3.3.2 FERIMET

The overall objective of Ferimet activities is to develop a procedure to maximise the magnet extraction and, therefore, recoverability of magnets from WEEE.

The three types of magnets to be recovered are: bonded NdFeB, bonded Sr-ferrite and sintered Sr-ferrite. The input flow from Ferimet was studied and an assessment on the different types of magnets that could be found was carried out with the help of the other pilot partners. The conclusion was that mainly two types of magnets were used in Electronic and Electrical Equipment, ferrite based and Neodymium based magnets.

Different batches of recovered magnets to be reused were sent to IMDEA for them to be the next actuator in the value chain and assess its reusability.

Additionally, the recovering tasks and extraction form the WEEE were manually performed, and with the support of EUT's robotic team (see previously), automation studies were carried out.

Regarding CELSA's input, representing the corporate activities from Celsa Group, they have provided support in the carried-out activities. With main focus on data related activities, such as input for the different models or Digital Product Passport (DPP).

3.3.3 IMDEA

The role of IMDEA in WEEE for magnets pilot is to experiment different process involved in recycling of magnets and optimise the process of recycling. The pilot is designed in a such a manner that there is supply of magnets obtained from waste electrical and electronic equipment that needs to be recycled. This process is carried out by FERIMET as is described earlier. There are typical two classes of magnets used in the electronic and electrical equipment, the ferrite-based magnets and Neodymium based magnets (NdFeB). These magnets are made typically in two broad ways, the sintered magnets and polymer bonded magnets. The sintered magnets possess good magnetic strength ((BH)max40 kJ/m3 – 300 kJ/m3) and are used for high energy motor applications. The cost of making these sintered magnets is high owing to many highly energy intensive steps involved in making these magnets. The magnets also can be prepared by adding polymer to make flexible magnets in different shapes. These magnets are used in relatively lower energy applications (electrical motors for low energy applications) when compared with the sintered magnets.

3.3.3.1 Recycling magnets

This section deals with the class of magnets that are focussed in the Plooto project. The magnets that are processed in Spanish pilot are sintered ferrite magnets and polymer bonded NdFeB magnets. We have received two batches of magnets from Ferimet (named as batch-1 and batch-2). The end-of-life batch-1 magnets were obtained from microwave magnets. The quantity of batch-1 magnets we obtained was 1 kg. The batch was processed for recycling process. The recycling of magnets was performed with five important steps involved in it. The initial steps involved in the optimization of the recycling process of ferrite magnets are shown in the figure. According to this process, we have started processing the magnets received.

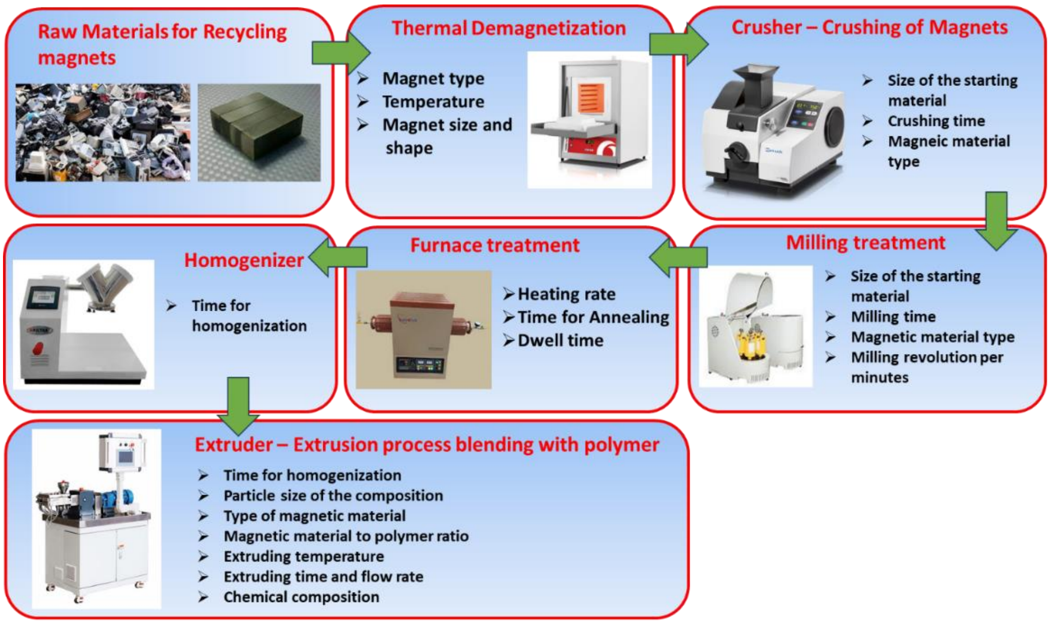

Figure 10: Steps involved in the recycling process of Batch-1 magnets

To describe the piloting activities, here we give details of experiments performed for recycling process of the first batch:

1. *Recording the properties of the Batch-1 magnets obtained Ferimet*

As discussed earlier, the Batch-1 end of life magnets were obtained from microwave Owen. The magnetic properties of the magnet were recorded. There are four important parameters as far as the magnet are concerned: the **saturation magnetization** M_S, **Remanence** B_R, **Coercivity** H_C and **strength of the magnet** $(BH)_{max}$. The values of the as obtained magnets were 70 Am²/kg, 38 Am²/kg and 176 kA/m.

2. *Thermal Demagnetization of Batch-1 Magnets*

The thermal demagnetization of the magnets was performed at 550°C/1hr. The total quantity of the magnets was 1 kg.

3. *Crushing of Batch-1 magnets*

The Batch-1 magnets were crushed using a jaw crusher. The sizes of these magnets were reduced to 1 μm at the end of the crushing process. Subsequently the resultant product was named as Batch-1B.

4. *Milling treatment of the Batch-1B magnets*

The milling of the magnets was performed using one particular condition as written below:

Specification for milling:

- 250 ml jar
- 100 balls stainless steel balls of 10 mm diameter.

The B2P (Ball to powder) ratio used was 10, thus for every 50 g 100 stainless steel balls were added.

First batch consisted of 1 kg of EoL magnets and was processed in sub-batches of 50g at 400RPM for 5 hours. At this point the magnets have been transformed into powder.

5. *Furnace treatment*

The 1 kg of Batch-1B powders was treated in a furnace at 1000ºC/1 hour. The furnace treatment helps to enhance the magnetic properties of the powder.

6. *Homogenizer*

This step is needed to make bonded magnets. The polymer is mixed along with the furnace treated Batch-1B powders. The homogenization of the powders was performed for 45 minutes.

7. *Extruder*

The powders were subjected to extrusion in order to obtain the final product: **pellets**. The conditions employed to perform extrusion are given below:

- 70% Ferrite – 30% polymer, also 0.1 wt% of wax was added to the mixture
    - There are four zones of temperature and one pre drying zone. The parameters used were:
    - Pre drying temperature and time: 100ºC/ 5 H
    - Zone 1: 260ºC
    - Zone 2: 270ºC
    - Zone 3: 275ºC
    - Zone 4 (mould temperature): 80ºC
- Pressure: 60 bar
- Velocity of the motor: 80 mm/s
- 80% Ferrite – 20% polymer

3.3.4 IMA

The role of IMA in WEEE for magnets pilot is different processes:

- Produce the final magnets.
- Recycle scrap bonded magnets.

For the first process, the magnets must be manufactured using different secondary raw material possibilities:

- Recycle scrap bonded magnets (all this process by IMA).
- Using the bonded materials (pellets produced by IMEA), according to the IMDEA's activities explained before.

For the IMA **process producing magnets**:

- A part reference was selected to be able to perform tests and have values to report.
- The Mold with 4 cavities to inject bonded ferrite.

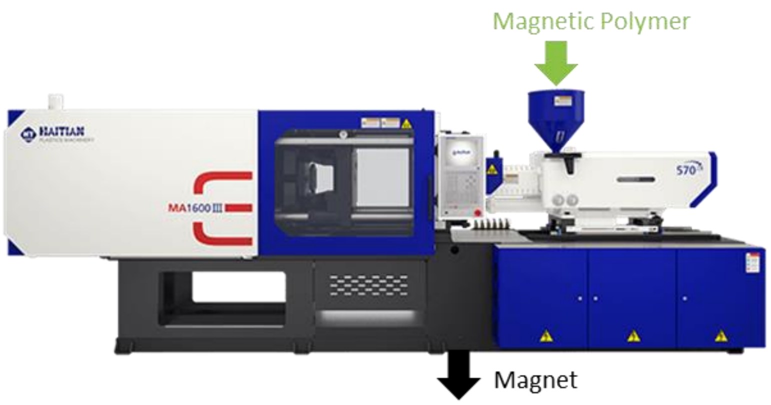

Figure 11: Injection equipment

For the first trials:

Values for 1 shift

1 shift
3000 pcs/shift
750 (x4 pieces) / shift
30 s (approx.) (x 4 pieces)

Material consumption
22 g (x 4 pieces)
16,5 kg / shift
Material / piece
1,6 g / piece
4,8 kg / shift

Values for 1 day (2 shifts):

1 day
6000 pcs/shift
1500 (x4 pieces) / shift
30 s (approx.) (x 4 pieces)

Material consumption
22 g (x 4 pieces)

33 kg / shift
Material / piece
1,6 g / piece
9,6 kg / day

Values for 1 month:

1 month
120000 pcs/shift
30000 (x4 pieces) / shift
30 s (approx.) (x 4 pieces)

Material consumption
22 g (x 4 pieces)
660 kg / shift
Material / piece
1,6 g / piece
192 kg / month

Minimum quantity of Scrap per month: 1600 pieces, that means around 12%

For the IMA **process recycling scrap magnets**:

- First of all, we need to demagnetize the bonded magnets.
- Then the crusher can prod.

About dealing with the scrap material, the first step is demagnetizing the pieces.

Figure 12: Magnetizer and demagnetizer equipment

And then we can crush them in pieces like pellets that we can inject again, so the pellets are ready to go to the injection process.

Figure 13: Crusher equipment

3.4 Results and KPIs Achieved

The results from the piloting activities for the magnets pilot can be observed in the implementation of various tools on the Plooto platform. The platform has primarily been developed for Ferimet and IMDEA, where collaboration was established. Data ingestion is functional, and the data is being utilized on the platform to display the companies' digital twins, along with the implementation of their DPP.

For the data ingestion, different interfaces were developed for each partner in order to upload manufacturing and material data to the platform through a set of templates which are easy to fill. The data is stored in an intermediate data lake where first data processing can be performed, and then the data is transferred to the Plooto platform to be used by the different services. A more detailed description can be found in D2.3 previously submitted.

Within the Plooto's platform, we can see data sources for each manufacturing step and material. These data sources are related with the physical assets defined in the platform. The connection between the different physical assets forms a network that can be visualized together with their last telemetries as can be seen in Figure 14.

Figure 14: Network summary for IMDEA

The establishment of collaboration can be used to share telemetries from shared assets, but also serves for the DPP. The first template for Ferimet and IMDEA is prepared and both companies are already sharing data as can be seen in one DPP record in Figure 15.

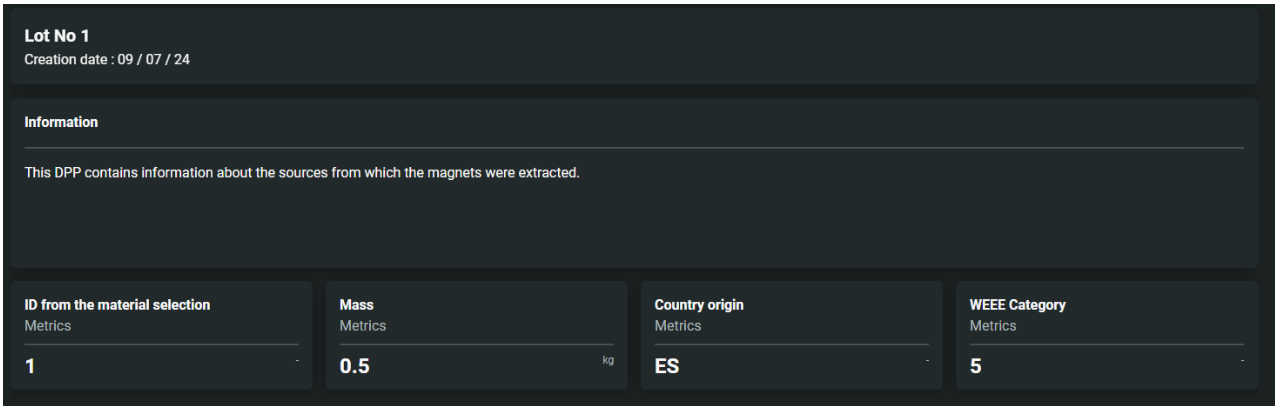

Figure 15: DPP Record for Ferimet

3.5 Lessons learned and challenges

Establishing a new supply chain presented greater challenges than initially anticipated, highlighting that even minor adjustments necessitate a robust support system. A key takeaway from this experience is the critical need for formal approval processes for any modifications, as these processes are vital to preserving quality and consistency.

When evaluating new materials, comprehensive data acquisition is essential. This includes information on magnetic and mechanical properties, in addition to other specifications outlined in the datasheet and Safety Data Sheet (SDS). Access to such detailed information facilitates informed decision-making and seamless integration of new materials into existing processes.

Furthermore, the approval process for new raw materials necessitates collaboration with both internal stakeholders and prospective customers to ensure joint approval. This collaborative approach guarantees that materials fulfil the standards and requirements of all parties involved.

This initiative underscored the importance of meticulous planning and comprehensive stakeholder engagement throughout the supply chain and materials selection processes.

4 Pilot 3: CFRP WASTE FOR DRONES

4.1 Pilot Description

The Italian pilot focuses on the reuse of carbon fiber reinforced polymer (CFRP) waste in drone manufacturing, involving a consortium of four key partners. HP Composites S.P.A (HPC), a leading company in the industry, generates a substantial amount of uncured prepreg scraps annually, which are then sent to CETMA Composites SRL (CC), an SME that transforms these scraps into CFRP composite material products. Acceligence (ACCELI) further utilizes these materials from CC for the production of UAV prototypes. Additionally, the CETMA Research Centre contributes its expertise in carbon fiber, thermoplastics, and recycling, developing innovative procedures to extend the shelf life of CFRP waste. The overarching goal of this collaboration is to significantly reduce CFRP waste and increase its reuse in drone manufacturing.

Figure 16: CFRP Waste Reuse Process for Drone Manufacturing

4.2 Objectives and expected outcomes

The pilot primarily aims to **enhance the reuse of Carbon Fiber Reinforced Polymer (CFRP) waste** generated during manufacturing processes, specifically focusing on uncured prepreg scraps. The project seeks to achieve this by developing a system of interconnected Cognitive Digital Twins (CDTs) to monitor and optimize various stages of the production process, from waste pre-processing to the final assembly of drones. Furthermore, the use of the Plooto Dataspace ensures effective data management and the certification of expired prepreg materials. Expected outcomes include a reduction in CFRP waste, shorter lead times, lower energy consumption, and the creation of a drone passport that details materials, standards, and origins. Ultimately, the Italian pilot exemplifies a circular economy approach by transforming CFRP waste into valuable resources for drone manufacturing, thus reducing environmental impact and promoting sustainable practices in the industry.

The expected outcomes of this pilot include:

- **Extended prepreg shelf life**: Increasing the usable lifespan of prepreg from 6 months to 12 months.
- **Reduced prepreg disposal**: Decreasing prepreg disposal at HP Composites from 30 tons/year to 10 tons/year.
- **Increased value of uncured prepreg scraps**: Shifting the value of uncured prepreg scraps from a cost (-300€/ton) to a potential revenue source (+300€/ton) for HP Composites.
- **Job creation**: Generating 5 new jobs in partner facilities specifically related to the utilization of uncured prepreg scraps.

- **Reduced CFRP waste**: Achieving at least a 20% reduction in unused CFRP waste during the production of composite materials.

These outcomes highlight the pilot's focus on promoting sustainability and resource efficiency in the manufacturing sector by transforming CFRP waste into a valuable asset, thereby contributing to a circular economy model.

4.3 Pilot Operations

The first iteration of Pilot 3 focused on validating the Plooto system's functionality and effectiveness in a real-world environment. This involved conducting per-operation trials and executing test scenarios to assess the system's performance in managing CFRP waste and facilitating its transformation into usable materials for drone production. Throughout this process, we trace each material type via its code, which includes information on both fiber type and resin type. Importantly, the re-qualification process does not alter the material but only extends its shelf-life. The specific operations carried out at each pilot site are detailed below.

4.3.1 HPC

HP Composites (HPC) was engaged in piloting activities aimed at optimizing the handling and transformation of uncured prepreg waste within the Plooto framework. The goal was to test and validate methods for enhancing circularity in carbon fiber reinforced polymer (CFRP) composites production, reducing waste, and improving the use of secondary raw materials (SRMs). HPC acts as waste supplier along the CFRP value chain. Two different kinds of waste can be identified: expired prepreg rolls and prepreg scraps coming from the cutting phase. Both consist of carbon fiber reinforcements impregnated with thermosetting resins.

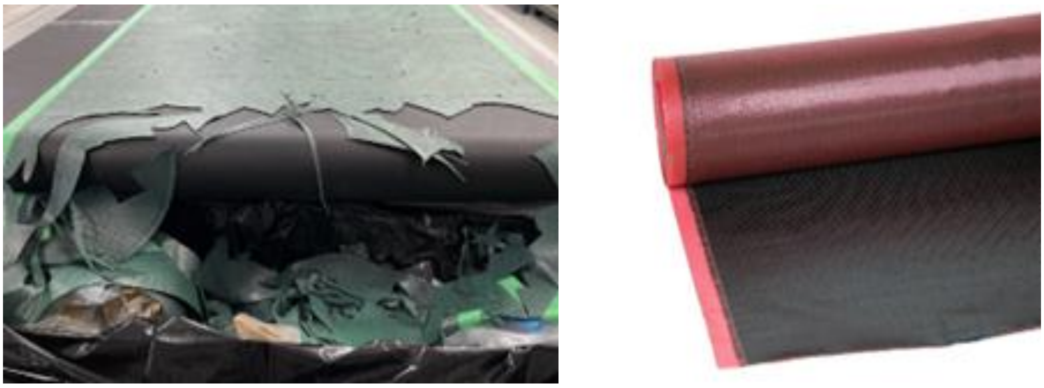

Figure 17: Prepreg cut-outs on the left and prepreg roll on the right

The scraps coming from the cutting phase have been reprocessed thanks to an innovative technology developed by HPC. HPC manages around 30-40 tons of uncured prepreg waste annually, and through the Plooto project, this amount is aimed to be significantly reduced by requalifying these materials.

Figure 18: Prepreg cut-outs reprocessing line

The main activities carried out by HPC can be synthetized in:

a. **Assessment and Characterization of Prepreg Waste Streams**
   - HPC began the pilot with a comprehensive assessment of the uncured prepreg waste generated at its facilities. This included cataloging the types, quantities, and specific properties (e.g., resin type, fiber content, shelf life) of prepreg scraps. This initial analysis provided the foundation for designing targeted waste management and recycling protocols.
   - The data were fed into Plooto to ensure traceability and transparency in material handling, allowing for an accurate understanding of the material flow within HPC's manufacturing ecosystem.

b. **Material Clustering and Traceability**
   - To reduce the number of types of prepreg cut-outs to be managed, HPC implemented a material clustering strategy, grouping the recovered prepreg scraps based on compatible resin systems, fiber types, and areal weights. This step ensures that materials with similar properties are processed together, maximizing the quality and consistency of the final products.
   - To manage the traceability of the material through each processing step, HPC meticulously documented the thermal history and other critical parameters. This ensured that each batch of material was traceable from the point of origin through to its transformation.

c. **SRM Recycling Process**
   - HPC exploited a proprietary innovative mechanical recycling technology designed to sustainably and cost-effectively reuse uncured CFRP cut-outs. The technology aimed to ensure minimal material degradation while optimizing the reuse of scraps.
   - The process begins with the arrival of prepreg waste at HPC's recovery line. Scraps are first resized at a cutting station, where they are cut into chips with regular, primarily rectangular shapes. The dimensions of these chips depend on the machine setup, and

the uniformity of shape is crucial for further processing. Following the cutting stage, the resized chips are transferred into a peeling station's hopper. Here, the protective films covering the prepreg material are removed through a peeling mechanism. The removed films are directed into a recycling system via an aspiration duct, ensuring minimal waste disposal and maximizing material recovery. At the exit of the peeling station, batches of peeled chips are collected for further use in manufacturing new products. An automated vision control system inspects these chips, ensuring that they meet quality standards and that any defects are identified early in the process.

Figure 19: Reprocessed prepreg cut-outs

d. Implementation of Plooto Platform

- HPC integrated Plooto Platform into its production environment to digitally map the uncured prepreg materials waste. The Platform provides insights into the status, conditions, and potential uses of materials based on collected data.
- HPC configured the Plooto platform to monitor and record each step of the waste management process. The traceability system captured data from when waste is generated at HPC's facilities to the final reprocessing.
- To ensure compliance and transparency, the platform generated a digital "passport" for each batch of material, containing information such as its origin, resin and fiber type, storage history, etc. These passports provided the necessary documentation for traceability and certification, meeting regulatory and industry standards.

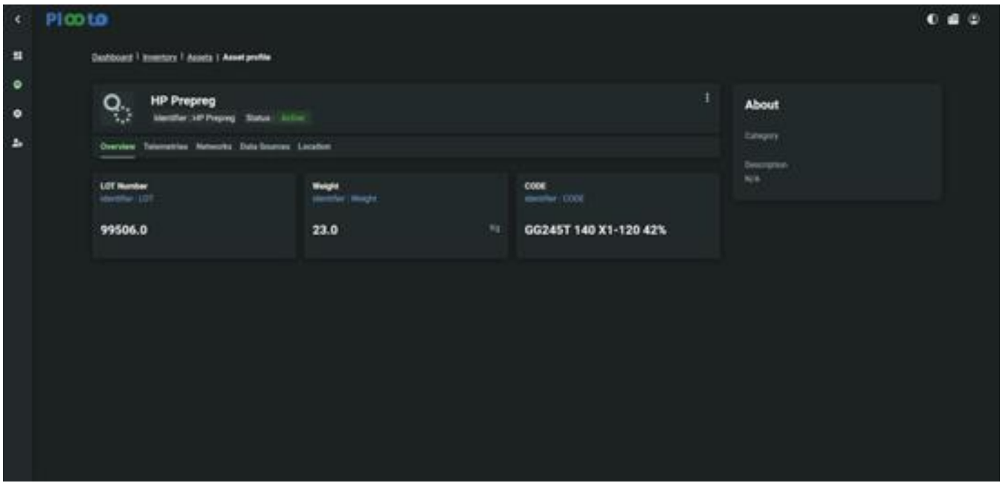

Figure 20: Example of a DPP for an expired prepreg roll.

e. Development and Testing of Requalification Protocols

- HPC collaborated with CETMA to develop protocols aimed at extending the shelf life of uncured prepreg materials.
- Pilot-scale testing was conducted to evaluate the effectiveness of these protocols. Tests verified whether the requalified material retained sufficient quality for reuse in secondary applications, such as drone components.
- The development of these protocols required iterative phases where adjustments were made based on the results of achieved. HPC ensured that the recycled prepreg materials met industry standards for composite integrity, strength, and safety through detailed evaluations and compliance assessments.

f. Integration and Collaboration with Supply Chain Partners

- A core aspect of HPC's pilot activities involved collaboration with other Plooto consortium partners, including CETMA, CETMA Composites and Acceligence. The goal was to create an interconnected supply chain where HPC's processed prepreg waste could be efficiently transformed into new composite components for drones.
- HPC implemented the Plooto platform's tools to enhance transparency and trust among partners. These tools recorded each step of the prepreg waste management process, from initial characterization and treatment to final conversion into drone components. This ensured that all parties had access to accurate, real-time data, promoting coordinated decision-making.
- Regular technical meetings were organized to align the processes across different facilities, ensuring that the quality standards and handling protocols were consistent throughout the supply chain.

g. Validation and Scaling of Circular Processes

- The validation phase included compliance assessments enhancing the trustworthiness of the circular processes and enabling traceability for end users.

Outcomes and Lessons Learned

- **Material Efficiency Gains**: Through the application of Plooto platform and optimized recycling protocols, HPC is able to successfully reduce its prepreg waste. This achievement demonstrates the potential of digital tools and data-driven decision-making in maximizing material efficiency and reducing environmental impact.
- **Scalability of Developed Protocols**: The protocols for extending shelf life and repurposing prepreg materials are proved scalable and adaptable to different composite manufacturing lines. This scalability opens opportunities for expanding the application of these protocols to other industries within and beyond the consortium.
- **Integration of Traceability and Compliance Tools**: The pilot is validating the effectiveness of the Plooto platform. Each material batch's info, from waste generation to repurposing, is documented, ensuring compliance with regulatory standards and facilitating transparent communication across the value chain.
- **Improved Collaboration and Knowledge Sharing**: Collaboration with supply chain partners and the use of integrated digital systems fostered a deeper level of cooperation and knowledge sharing. The pilot highlighted the importance of transparent data exchange and shared objectives in achieving circularity goals.

Next Steps

- HPC plans to scale up the developed protocols and Plooto applications across its entire production line, aiming to integrate these circular practices as standard operations.
- Future efforts will focus on possibly enhancing the CDT models by incorporating advanced algorithms for predictive capabilities, enabling resource optimization and waste reduction.
- HPC also aims to collaborate with other sectors of the Plooto project to apply similar waste management strategies in varied contexts, further promoting circular economy principles.

4.3.2 CETMA

The overall objective of CETMA is to develop a procedure to evaluate the usability of prepreg waste for composite production and, hence, to extend prepreg shelf life.

Prepreg waste mainly consists of two different types, expired prepregs and prepreg scraps. Expired prepregs consist of carbon fiber reinforced prepreg in form of unopened or partially used rolls. Prepreg scraps derive from cutting operations in the form of uncured off-cuts, skeletons, trim waste and end-of-roll waste.

Both waste types are composed by a carbon fiber reinforcement and a thermoset resin that undergoes, during prepreg life, a progressive and irreversible cure reaction that alters its physochemical properties and, hence, prepreg handling and processing behaviour. For this reason, prepreg manufacturers indicate the allowable prepreg storage time at room temperature (called out life) and at freezer temperature, -18°C, (called shelf life) beyond which prepregs are no longer usable due to the fact that the composite mechanical performances are no longer assured. Actually, beyond out and storage life, prepregs are considered expired and disposed of in landfills.

By defining a simply and cost-effective requalification procedure, out life and shelf life of prepregs waste can be extended. The requalification procedure developed by CETMA is composed by two main processes; the first one, defined as *usability evaluation*, allows to sort prepreg waste to be disposed and that can be used as secondary raw materials (SRM). Those ones go through a second process, called *process window definition,* that allows to define the processing parameters for composite production and the new expiry date.

The *usability evaluation procedure* is only applicable to expired prepregs waste and is based on measurement of multiple parameters through which is possible to monitor the material aging state.

As widely demonstrated in literature [9], prepregs aging consists of a slow but progressive cure reaction between epoxy resin and crosslink agent that increases the resin system crosslinking. The crosslinking rate of the resin system could be determined through thermal experiments on uncured prepreg waste and, in particular, through the measurement of the following parameters:

- Conversion degree of curing reaction (α): this variable is a representation of how far the chemical curing reaction has advanced describing the physical state of the thermoset resin as it transitions from a flowing resin into a solid matrix. During uncured prepreg aging, cure degree tends to increase from 0 to 100%, that indicates that the resin matrix is completely cured. Curing degree is described by the following equation:

  $$\alpha = \frac{\Delta H_T - \Delta H_E}{\Delta H_T}$$

  Where ΔH_t is the enthalpy of the not-expired prepreg and ΔH_E is the enthalphy of the expired prepreg.

- Glass transition temperature (T_{g0}): this parameter measures the glass transition temperature of the prepreg at 0% cure. It reflects the crosslink density of the uncured resin system, where the more extensive its crosslink network is, the higher the observed Tg_0.

Both parameters are measured by Differential Scanning Calorimetry (DSC) analysis applying a dynamic heating to the materials from 25°C to 250°C at a 20°C/min.

Resin crosslinking reduces the molecular mobility of the polymeric chain causing an increase of resin viscosity and a reduction of the resin capability to flow into the carbon fibers tows. This could lead to composite components characterized by high level of porosity that, hence, determine a reduction of the mechanical performances of the composite.

For these reasons, it is crucial to evaluate the microstructure of the composite by measuring its voids content (V_c) and some of its mechanical performances. Voids content indicates the percentage of voids in the composite volume and, for an ideal composite, it should be close to zero. Regarding mechanical performances, as widely described in scientific literature [10][11], one of the most important parameters is the interlaminar shear strength (ILSS) that measures the shear strength between laminate planes of the composite.

By measuring discriminating parameters repeatedly during the material aging (considering the non-expired material data as a reference), it is possible to find out a correlation between them that can be used to verify the usability of the waste material simply by measuring one of the discriminating parameters. The aim is to determine the usability of an expired prepreg only by measuring its thermal properties (T_{g0} and α), due to the fact that DSC analysis is the most easy and cost-effective test.

As the expired material or its stocking conditions varies, it is necessary to develop new correlation curves by repeating the usability evaluation procedure.

In order to decide if an expired prepreg is still usable, a classification criterion has been chosen on the basis of scientific literature and experience (Table 3). This theoretical criterion may be subject to change as a result of the experimental activities performed on prepreg waste supplied by HPC and feedback from other partners of the pilot.

Table 3: Criteria for expired prepreg classification.

Usable material	If material has *V_c <10% and ILSS deviates less than 15% from the reference value* (ILSS of not-expired prepreg) is still usable by using the same processing parameters of the reference material.
	If material has • *10%<Vc<15% or* • ILSS deviates between 15% and 25% from the reference value (ILSS of not-expired prepreg) Is still usable by determining new processing parameters.
No usable material	If material has • *V_c >15% or* • *ILSS deviates more than 25% from the reference value* Is no more usable and has to be disposed.

The *process window definition* step consists in finding the suitable parameters for uncured prepreg waste processing, both in form of expired rolls and cutting scraps.

Prepreg processing is a critical step during the production of a composite component that consists of curing and consolidation of the uncured prepreg. The most important parameters to be set are temperature, pressure and time; those parameters affect the rheological behaviour of the thermoset resin, its flow capability into the tow of the reinforcement and, hence, the physical and mechanical performances of the final composite component.

It is easy to understand that prepregs waste, due to their altered thermal, physical and mechanical performances or changed geometry (in case of scraps), may need to be processed with different parameters than those of the corresponding non-waste materials, in order to restore their original physical and mechanical performances.

To determine the new processing parameters, Cetma use an experimental approach following these steps:

1) Searching of the new processing parameters:
    - Temperature (°C): defined through thermal gravimetric analysis (TGA)
    - Time (min): defined through DSC analysis
    - Pressure (bar): that is modified step by step during the experimental tests.
2) Evaluation of the physical and mechanical performances of the composite obtained applied the new processing parameters, as V_c and ILSS, and comparison with the reference values (non-expired material).

The procedure may require iterative phase and is repeated until $Vc<10\%$ and ILSS varies less than 15% from the reference value; once this condition has been reached the material is requalified. If the expired material meets the aforementioned condition during the *usability evaluation process*, the processing parameters are those of not-expired prepreg (available in technical data sheet of the material).

4.3.2.1 Application of the requalification procedure to prepreg waste materials

In order to validate the requalification process, CETMA has applied the procedure to an expired prepreg waste supplied by HPC. Material data from HPC are resumed in the following table:

Table 4: Information on expired prepreg provided from HPC

Code	GG245 140 X1-120 42% H1400
HPC_Lot Number	99506
Expiry Date	06/12/2023
Stocking temperature after expiration	-18°C

By applying the usability evaluation process, the discriminating parameters (Tg_0, α, ILSS and V_c) are measured. The discriminating parameters measurement is repeated periodically in order to monitor the material aging. In particular, until now, data were collected on the expired material stocked at -18°C for 2, 6 and 9 months (F2, F6 and F9) after the expiry date (Figure 21).

By comparing data of the expired prepreg, even after 9 months from the expiry date (F9), with those of the reference (F0), it results that V_c is lower than 10% and ILSS deviates less than 15% from the reference value of the not-expired material (F0).

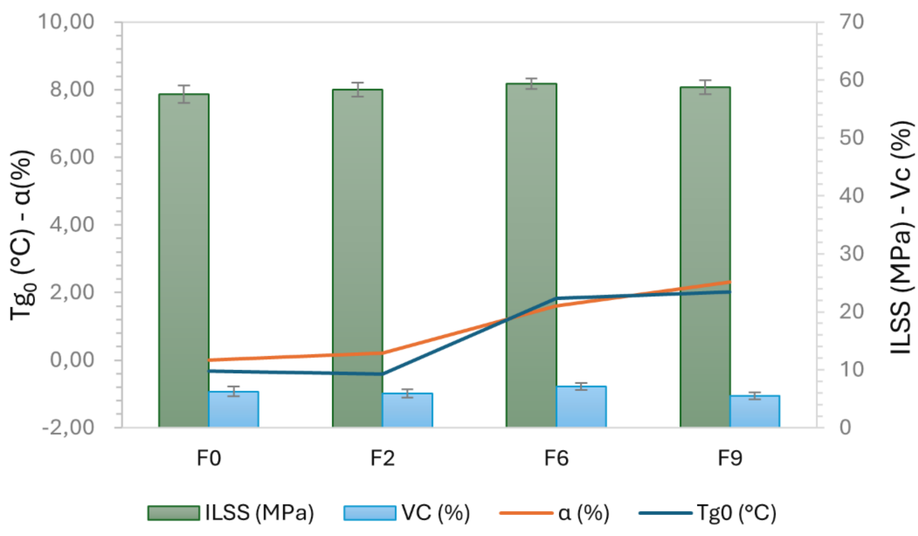

Figure 21: Relation between discriminating parameters of the expired prepreg analysed

Table 5: Relation between discriminating parameters of the expired prepreg analysed

	Tg_0 (°C)	α (%)	ILSS (MPa)		VC (%)	
			media	dev.st	media	dev.st
F0	-0,32	0	57,51	1,49	6,25	0,89
F2	-0,42	0,2	58,32	1,23	5,89	0,74
F6	1,83	1,6	59,35	0,92	7,09	0,63
F9	2,01	2,3	58,7	1,23	5,5	0,59

This means that expired prepreg, after 9 months from the expiry date, is still usable by using the same processing parameters of the reference material.

In Table 2, processing parameters and new expiry date of the material is reported. The expiry date indicated is purely indicative because the usability evaluation process is still on-going.

Table 6: Requalified material data

Code	GG245 140 X1-120 42% H1400
HPC_Lot Number	99506
CETMA_Lot Number	99506R
Processing Temperature (°C)	130
Processing Pressure (bar)	6
Processing Time (min)	90
New Expiry Date	06/09/2024

4.3.2.2 Current status

The activities performed in the last part of the period concern the integration of the requalification procedure on the Plooto platform. CETMA configured the platform to record and track the data related to the process of prepreg waste requalification.

To ensure compliance and transparency, the platform generated a digital "passport" for each batch of material waste supplied by HPC and subjected to the requalification procedure, containing information such as its origin, resin and fiber type, storage history, processing parameters, new expiry date. These passports provided the necessary information for traceability and certification, meeting regulatory and industry standards.

A preliminary example of a DPP of a requalified material is shown in figure 24 and is integrated and accessible from the Plooto platform.

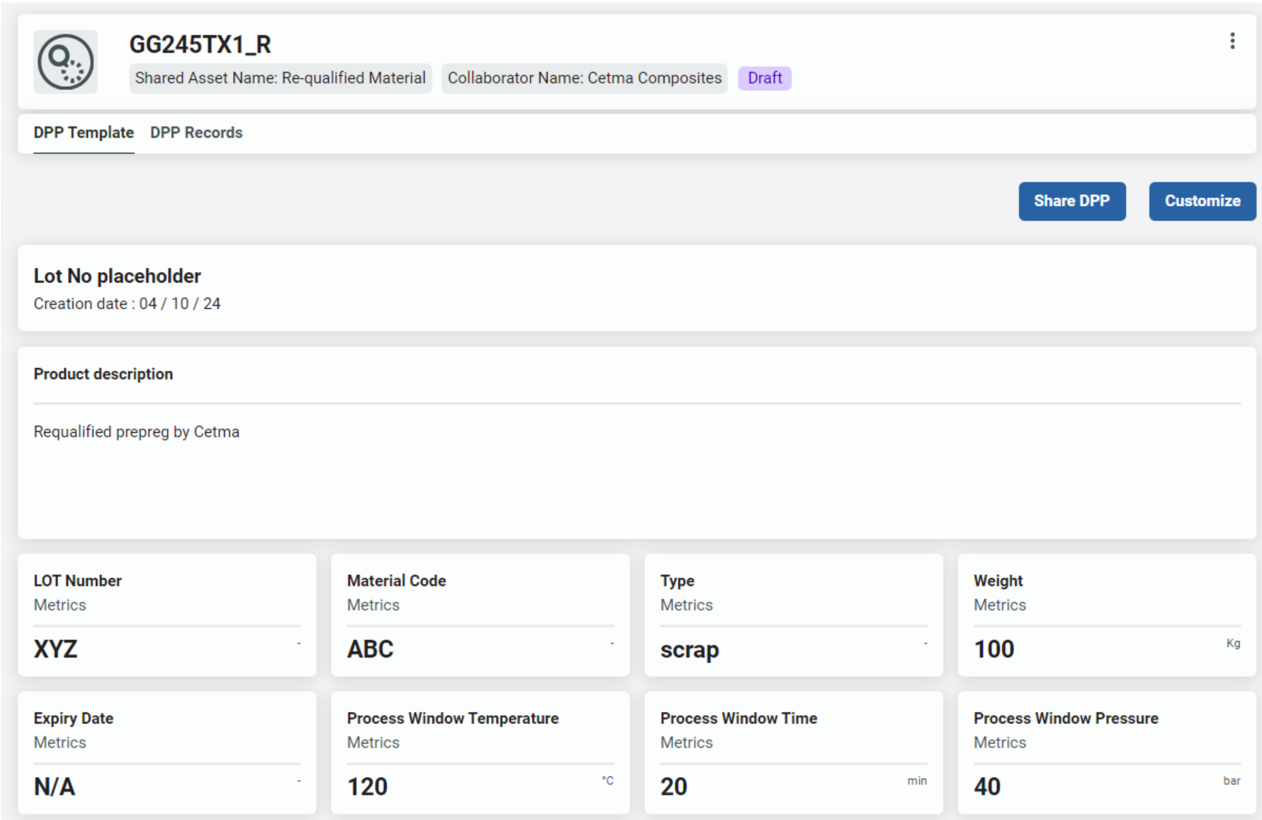

Figure 22: Example of a DPP of a requalified expired prepreg

4.3.3 CC

The work carried out from CC can be divided in five main activities:

- identification of critical parameters and factors relevant for the production of parts with re-qualified prepregs;
- development of equipment for acquiring real time data available on-line;
- collecting of historical data for development of optimization and digital twin models;
- identification of factors that are relevant for costs and environmental impact.
- production of first prototypes of components for drone

Identification of critical parameters

In this activity the main steps required for development and production of composite structures were identified and explained, focusing on the additional difficulties due to the use of re-qualified prepreg. Starting from explanation of issues related to general composite structures, the study was focused on the drone items under development in the project (see next image). This activity was fundamental in order to set up the right methodology for the models.

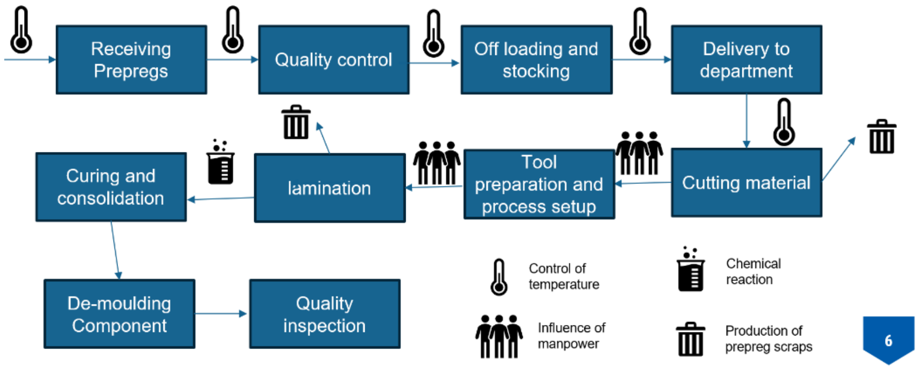

Figure 23: Scheme of production of composite components

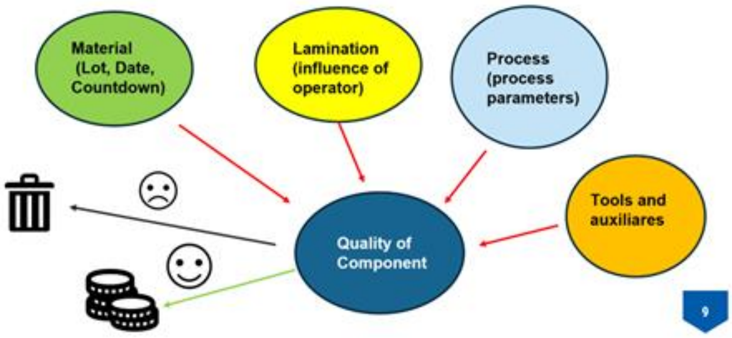

Figure 24: Relevant factors that influence quality of parts

The relevant factors were schematised in an excel file that was used to share data with other project partners.

Development of equipment for acquiring real time data available on-line

In this activity CC carried out the work for digitalization of manufacturing processes. The sensors required to acquire fundamental parameters (temperature, pressure, electric consumption) were identified. The procedure to put these parameters available on line was developed too.

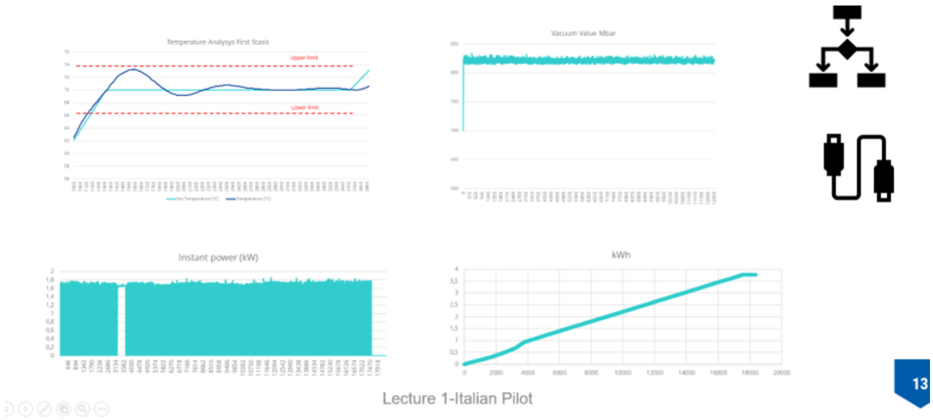

Figure 25: View of parameters during processing of composites

Collecting of historical data for development of optimization and digital twin models

In this activity CC collected datasets of processes reporting relevant data and parameters, to share with the partners developing optimization and digital twin models. For the models it was important to get enough realistic data that allow validation of results. In the example reported in next image different parameters like date, operator, tool conditions were acquired, together with curves of temperature, pressure and electric consumption.

PROCESS PARAMETERS FOR SANDWICH PANELS									
Cycle date	Item	Operator	PREPREG LOT	DAYS AFTER PREPREG PRODUCTION	tool	cycles after tool manteinance	Curve	quality result %	reason of defect
15/02/2024	M33402	CA	8-24	3	CH1	16	800	100	
20/02/2024	S311464	CA	8-24	3	CH1	17	806	100	
21/02/2024	LO41679	GA	8-24	4	CH1	18	808	0	operator
27/02/2024	S311508	CA	8-24	10	CH1	19	815	100	
28/02/2024	S311521	CA	8-24	11	CH1	20	817	100	
29/02/2024	M21590	LD	8-24	12	CH1	1	819	100	
01/03/2024	S311544	LD	8-24	13	CH1	2	821	100	
04/03/2024	LO41707	CA	8-24	16	CH1	3	822	100	
06/03/2024	M21592	DF	23-24	2	CH1	4	824	100	
07/03/2024	M21596	DF	23-24	3	CH1	5	825	100	
08/03/2024	S311567	DF	23-24	4	CH1	6	826	100	
11/03/2024	S311583	LD	23-24	7	CH1	7	827	100	
13/03/2024	S311599	CA	23-24	9	CH1	8	829	100	
15/03/2024	LO41743	LD	23-24	11	CH1	9	837	100	
18/03/2024	S311628	CA	23-24	14	CH1	10	838	100	
19/03/2024	S311646	GA	23-24	15	CH1	11	839	0	operator
20/03/2024	S311638	LD	23-24	16	CH1	12	840	100	
21/03/2024	M31603	CA	23-24	17	CH1	13	841	100	
22/03/2024	LO41761	CA	23-24	18	CH1	14	844	100	

Table 7: Example of dataset for model optimization

Identification of factors that are relevant for costs and environmental impact.

In this activity CC schematised and collected all the data related to costs and environmental impact of composite components for drone (cost and consumption related to manpower, process, tool, equipment). The differences between the use of virgin material and re-qualified prepreg were identified, collected and quantified for different items and for different manufacturing processes. All the data were collected in excel file and shared with optimization model developers. It is important to notice that the right selection among different re-qualified materials is crucial to obtain cost-effective components with low environmental impact.

	A	B	C	D	E	F	G	H
1	Body cover	Item #4						
2		width (mm)	length (mm)	height	thickness (mm)		Density	
3	Dimensions	600	175	82	1	densità	1,6	g/cm3
4								
5	Costs for material and trimming							
6	Component Weight [g]	290						
7	Overtrim	30%						
8	Prepreg need [g]	377			Total cost compression moulc	122,378077		
9	Layup X1-151 200gr/sqm (plies)	5						
10	Layup X1-151 380gr/sqrm (plies)	3						
11	Layup X1-151 630gr/sqrm (plies)	2						
12	Layup Imp503Z 240 gr/sqrm (plies)	4						
13	Layup Imp503Z 300 gr/sqrm (plies)	3						
14	Layup Imp503Z 630 gr/sqrm (plies)	2						
15	Layup Imp503Z 204 gr/sqrm (plies)	5						
16	Layup Imp509 380 gr/sqrm (plies)	3						
17	Layup Imp509 204 gr/sqrm (plies)	5						
18	Prepreg Cost X1 -151 200 gr/sqm [€]	27,1						
19	Prepreg Cost X1-151 380gr/sqrm [€]	26,4						
20	Prepreg Cost X1-151 630gr/sqrm [€]	35,8						
21	Prepreg Cost IMP503Z 240gr/sqrm [€]	30,8						
22	Prepreg Cost IMP503Z 300gr/sqrm [€]	39,6						
23	Prepreg Cost IMP503Z 630gr/sqrm [€]	36,5						
24	Prepreg Cost IMP503Z 204gr/sqrm [€]	29,6						
25	Prepreg Cost IMP509 380 gr/sqrm [€]	29,7						
26	Prepreg Cost IMP509 204 gr/sqrm [€]	30						
27	Total Prepreg cost X1-151 200 gr/sqrm[€]	18,49575						
28	Total Prepreg cost X1-151 380 gr/sqrm[€]	10,8108						
29	Total Prepreg cost X1-151 630 gr/sqrm[€]	9,7734						

Table 8: Collection of data for optimization model

Production of first prototypes of components for drone

In this activity first prototypes of composite components for drone were manufactured using digitalised processes. For this purpose, CC manufactured the tools required for production, and developed the set-up to collect data.

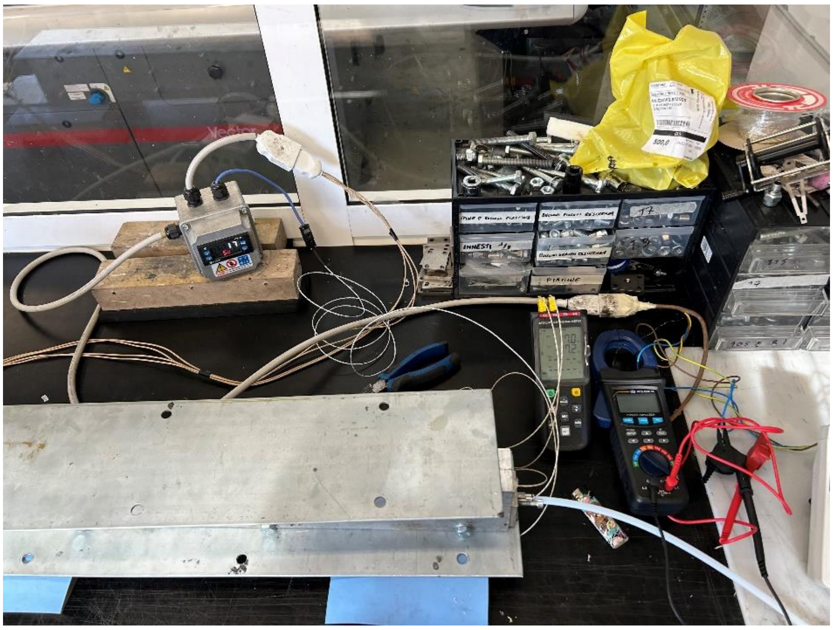

Figure 26: Manufacturing of composite tubes for drones using digitalised processes.

The CC activities of the last part of the period were related to the development of first demo and to the integration of data on the Plooto Platform.

4.3.4 ACCELI

The components in question are made of Carbon Fiber Reinforced Polymer (CFRP) and are key elements in the assembly of Unmanned Aerial Vehicles (UAVs). These parts are categorized into three main types, each serving different functions in the overall UAV design:

1. **Tubes** – These are structural elements with a standard cylindrical cross-section, and we are working with seven different types of tubes. These tubes play a critical role in providing structural support to the UAV's frame. Their lightweight but durable nature makes them ideal for maintaining the UAV's stability and strength, without adding unnecessary mass, which is crucial for flight performance.

2. **Plates** – These flat components come in four varieties, each with a standard thickness. In UAVs, plates are used for various structural and mounting purposes. They serve as platforms for securing critical systems such as avionics, sensors, or propulsion units, and also reinforce areas that experience significant mechanical stress during flight.

Custom Parts – These are highly specialized components, often comprising the **body covers** of the UAV. There are two different types of custom parts currently under development, and they are manufactured using molds. These custom parts typically include the **aerodynamic outer shell** of the UAV, which not only protects the internal systems but also enhances the aircraft's flight performance by minimizing drag and providing structural integrity. Due to their complex shapes and critical functions, these parts often require careful post-processing after being molded, such as CNC cutting to ensure precise fits for mounting and assembly.

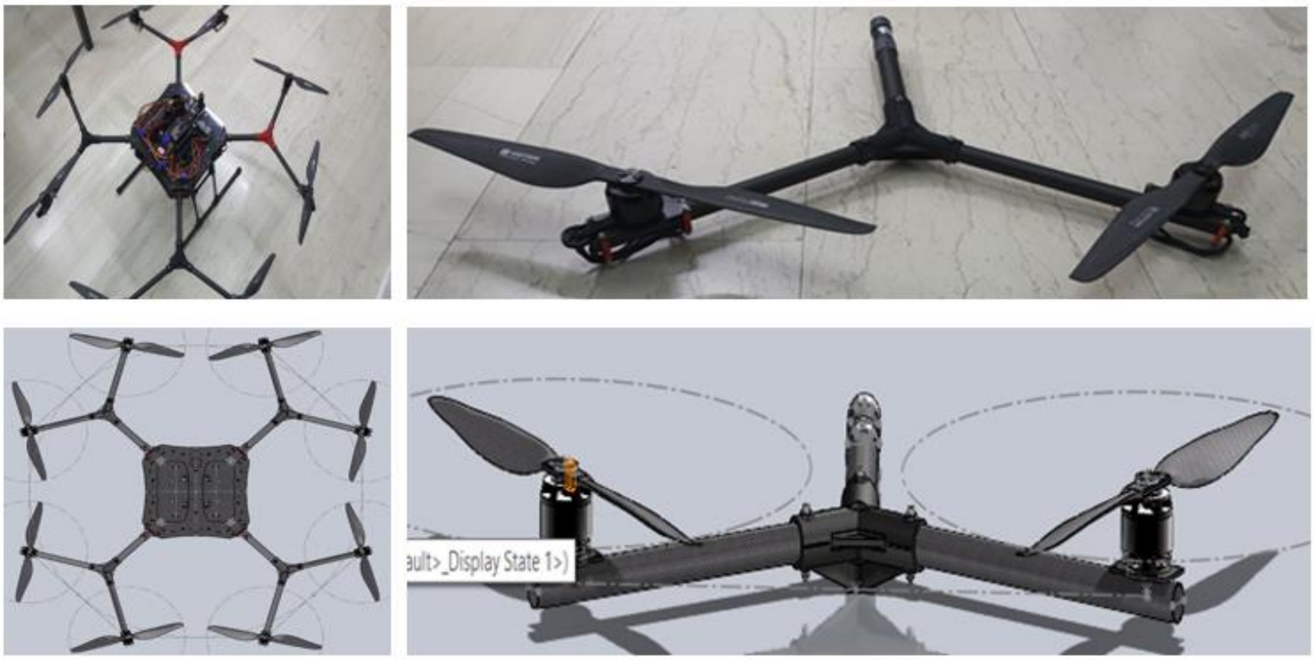

Figure 27: Design and Implementation of CFRP Components in UAVs

4.3.4.1 Challenges

The main challenge we face involves determining how much of the fabrication and post-processing work we should outsource for the **Tubes (1)** and **Plates (2)** categories. These components require additional **CNC (Computer Numerical Control) machining** after the initial manufacturing stage to achieve the precision needed for UAV assembly. The decision to outsource this machining or perform it in-house will have significant implications for production time, costs, and quality control.

We need to consider two primary options:

- **Outsourcing complete fabrication**: By providing the supplier with the full specifications, including the required CNC cuts, we could receive finished components that are ready for immediate assembly. This could streamline production but might increase our dependence on external suppliers, potentially raising costs and limiting flexibility for last-minute adjustments.
- **In-house post-processing**: In this case, we would provide the supplier with only the overall dimensions, receive raw parts, and handle the CNC machining ourselves. This approach gives us more control over the final product and allows for more flexibility during assembly. However, it could extend our production timeline and require more resources and expertise on our end.

For the **Custom Parts (3)** category, which typically includes the **UAV body covers**, the challenge is slightly different. These parts are manufactured using molds, and we must decide whether to have the supplier handle the entire process—from mold creation to post-molding CNC cutting—or whether to split the tasks between them and us.

If we choose to have the supplier handle the entire process, we must provide highly detailed designs to guide the mold creation. The supplier would then be able to fabricate the custom parts and perform the necessary CNC cutting. Alternatively, if we choose to take over the CNC processing, we would need to ensure that the parts received from the supplier are correctly molded but not fully finished, leaving the final precision cutting in our hands. This approach would give us control over critical aspects of the part's final fit and finish, especially for components like body covers, which require exact precision to ensure proper integration with other UAV systems.

4.3.4.2 Current status

We are currently finalizing how these decisions will be implemented within the Plooto platform, a key tool for managing and tracking our UAV components. This platform will play an essential role in organizing our supply chain, documenting the technical specifications of each part, and detailing the processing steps involved, from initial manufacture to final assembly.

To illustrate this point, the following table provides a sample of how UAV component data is structured and managed for the Plooto platform:

CERBERUS CFRP PARTS							
		Item Description	Outside Diameter (mm)	Dimensions (mm)	Thickness (mm)	Quantity	Remarks
1	Circular tube	Arm mount	30	95	1	4	
2		Main Arm	25	250	1	4	
3		Secondary arm	20	300	1	8	
4		Foot	20	580	1	2	
5		Leg	12	300	1	4	
6		Landing gear frame	12	323	1	2	
7		Landing gear frame	12	130	1	2	
8	Plate	Chassis Upper Plate	-	372x372	2.5	1	Maximum plate dimensions for the CNC milling: 700x550mm. For the nesting of the parts, please consider a margin of at least 10mm between the parts and 20mm at the edge of the plate, to facilitate its attachment on the CNC.
9		Chassis Lower Plate	-	372x372	2	1	
10		Arm mount Plate	-	88*60	2	8	
11		Motor Mount Plate	-	43*55	2	8	
12	Mold Parts	Y joint half	-	118x103x15	1.5	8	Exact Geometry shall be given in 3D drawing
13		Chassis shell	-	406x406x139	1	1	Exact Geometry shall be given in 3D drawing

Table 9: UAV Component Data for the Plooto Platform

This table demonstrates of the component's specifications, including dimensions, materials, and quantities. This information, originally compiled in a structured Excel sheet and then integrated with the Plooto platform.

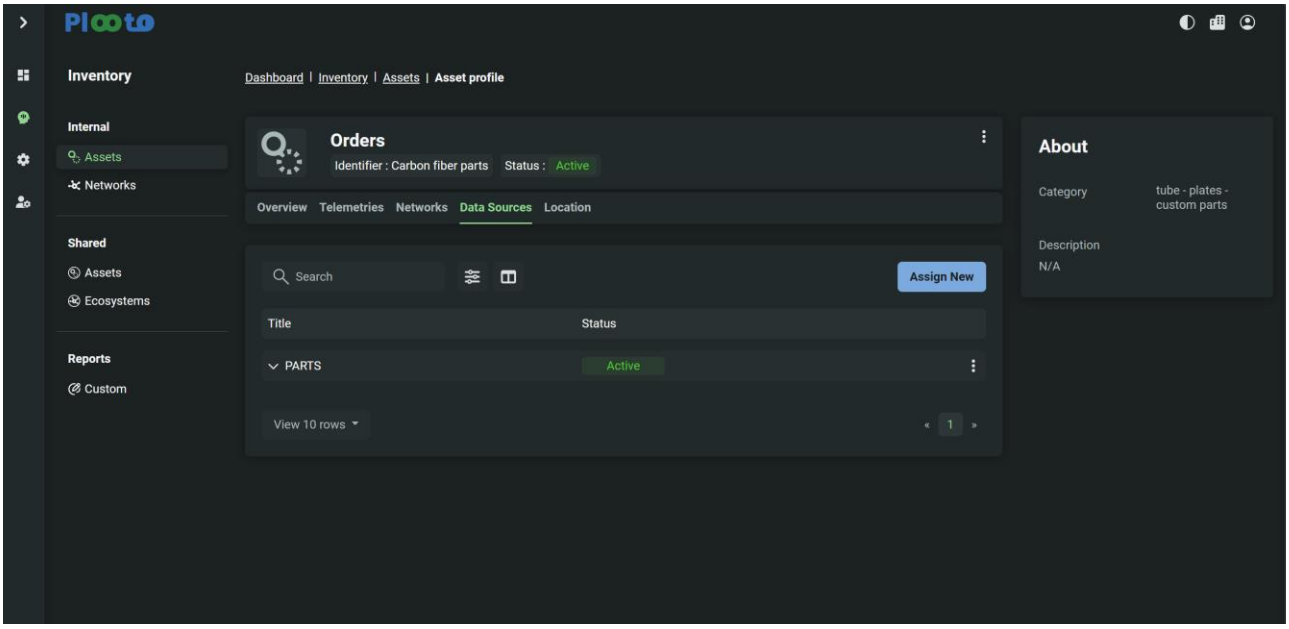

Figure 28: Example of Plooto platform

The decision to outsource the CNC machining or perform it in-house will also affect how our components are described and catalogued within the platform. This includes the need to accurately document not only the overall dimensions but also the post-processing requirements and any special considerations for assembly. These decisions will ultimately shape how we manage quality control, streamline production, and ensure traceability of each component throughout its lifecycle.

Moving forward, determining the right balance between outsourcing and in-house processes is critical, especially for components like UAV body covers, where precision and fit are vital for the aircraft's aerodynamics and overall performance. As we scale our production capabilities, these choices will influence both short-term efficiency and long-term scalability, allowing us to maintain a flexible yet consistent production line for various UAV models.

4.4 Results and KPIs achieved

The **prepreg shelf life** KPI aims to extend the usable duration of prepreg materials from six months to twelve months with the support of the Plooto platform. Prepreg materials have a limited shelf life due to the risk of degradation in their performance properties, which can reduce the quality of composite parts. By optimizing storage conditions, tracking environmental variables, and implementing data-driven best practices through Plooto, we anticipate being able to safely extend this shelf life by up to 100%. In terms of measurement, shelf life can be assessed by tracking and comparing the expiration dates of batches under the new system versus the previous baseline. Additionally, conducting quality assurance tests on materials at the six-month mark and beyond will verify whether the materials maintain their intended performance qualities. However, as this is a long-term metric, it requires consistent data collection over at least a year to begin establishing measurable improvements.

For **prepreg disposal in high-performance composites (HPC)**, we aim to significantly reduce waste, increasing disposal rates from 3 tons per year to 10 tons per year. This KPI is critical for reducing excess inventory and ensuring a more sustainable approach to materials management. To accurately measure this outcome, we would assess the total weight of discarded prepreg materials in annual increments, noting improvements in efficiency enabled by the Plooto platform's tracking and predictive analytics capabilities. With systematic reporting on waste disposal, partners can quantify progress towards optimized material usage. However, gathering a reliable dataset that reflects the typical disposal needs will take several cycles, meaning that immediate measurable results may not be achievable in the current phase.

The **value of uncured prepreg scraps for HPC** is projected to shift from a negative value of -300 euros per ton to a positive valuation of 300 euros per ton, signifying a shift from cost burden to value creation. Through Plooto, we plan to find uses for otherwise discarded materials, potentially repurposing them into secondary markets or alternative production applications. Measuring this KPI involves calculating the net value gained from repurposing scraps compared to the cost of disposal. This would include assessing market value for any secondary products derived from scraps, as well as direct cost savings. Establishing positive returns from scrap repurposing requires ongoing market engagement and a substantial dataset to support viable use cases, which we anticipate will take time to develop.

For **unused CFRP waste in the production of composite materials**, we are targeting a 20% reduction. As of now, unused CFRP waste has not been precisely measured, which makes this KPI foundational for understanding current waste levels and setting future reduction goals. Measurement would involve tracking unused CFRP materials as a percentage of the total materials purchased, allowing us to set benchmarks and assess improvements over time. Plooto's role will be to monitor production processes, identify inefficiencies, and suggest changes to reduce waste. Achieving a 20% reduction will require multiple iterations of optimization, as CFRP waste management improvements often depend on understanding complex production cycles, and this may not yield quantifiable results until later project stages.

As we are currently in the early stages of implementing the Plooto platform, we are not yet able to provide measurable outcomes for these pilot activities. The primary objective of this phase is to set and track key results against the KPIs. However, obtaining a comprehensive understanding of these outcomes requires consistent data collection over a sustained period—at least 1-2 years of pilot operation—before performance can be accurately evaluated. In the next version (v2) of this deliverable, we anticipate having a well-defined dataset, enabling us to provide a thorough assessment of the KPIs. This timeframe will allow for a realistic interpretation of Plooto's impact on extending prepreg shelf life, reducing disposal rates, increasing the value of prepreg scraps, and minimizing CFRP waste, aligning with the project's sustainability and performance objectives.

4.5 Lessons learned and challenges

During the pilot, one of the primary challenges encountered was maintaining consistent material quality across batches of uncured prepreg scraps. Variability in the properties of the waste materials, such as resin type, fiber content, and aging, led to difficulties in standardizing the recycling process and ensuring high-quality requalification. This inconsistency required frequent adjustments to processing parameters, increasing the complexity of operations.

Additionally, scaling the recycling process presented logistical challenges, particularly as larger volumes of waste were processed at different pilot sites. Coordination across the supply chain, from HPC's waste generation to UAV production at ACCELI, also introduced complexity. Despite the integration of the Plooto platform, aligning partners' schedules, quality controls, and ensuring timely material flows was difficult, particularly when delays in material availability occurred.

Furthermore, ensuring that the requalified materials met regulatory standards was another hurdle. Certification and additional testing were needed to guarantee the requalified materials' safety and performance, which added time and cost to the process.

In terms of lessons learned, the pilot highlighted the critical role of digital tools for managing waste materials. The integration of the Plooto platform for digital traceability was a key enabler, providing transparency and enabling collaboration across the supply chain. This ensured compliance with standards and streamlined communication between partners. Another important lesson was the need for flexibility in handling material variability. The ability to adapt processing parameters in real-time based on data collected from the Plooto platform allowed for greater control over material quality, reducing waste and improving efficiency.

Moreover, the pilot underscored the importance of cross-sector collaboration, as regular coordination between HPC, CETMA, and ACCELI was vital in overcoming operational and material challenges. The success of the pilot demonstrated the potential of these circular processes, not only in terms of environmental sustainability but also economic viability, as the requalified CFRP waste was successfully repurposed into valuable UAV components, transforming waste into a potential revenue stream.

5 Conclusions

5.1 Summary of findings

The pilots conducted under the Plooto project have demonstrated the potential for integrating circular economy principles across different industrial contexts. The reuse of CFRP waste for drone components, the recovery of magnets from WEEE, and the valorisation of citrus processing by-products have collectively shown how significant environmental and economic benefits can be achieved. The role of digital tools, particularly the Plooto platform, has been crucial in enhancing traceability, optimizing resource use, and ensuring regulatory compliance.

These pilots have revealed key lessons, such as the importance of flexibility when dealing with material variability, the value of real-time data for decision-making, and the critical role of collaboration between different sectors. The primary goals of reducing waste, generating value from secondary raw materials, and implementing sustainable processes have been successfully demonstrated.

This document serves as the first version of the pilots' deliverable, with initial insights and foundational analysis. In the next iteration, we will present in-depth analytical results, highlight achievements, and provide more comprehensive evaluations, thereby offering a deeper understanding of the project's long-term impacts and benefits.

5.2 Future directions for Pilots

Looking ahead, the next steps for each pilot will involve refining the developed processes, scaling them to full production, and investigating additional applications. For the CFRP waste pilot, further efforts will focus on improving requalification protocols to extend the shelf life of prepreg materials and reduce costs. The WEEE pilot will seek to enhance the recovery of magnets and expand the range of electronic devices targeted for recycling. The citrus waste pilot will continue to optimize the production of molasses and essential oils, with a specific focus on improving energy efficiency.

Additionally, the Plooto platform will be further integrated into each pilot, providing enhanced monitoring, real-time data collection, and predictive capabilities across the supply chain. This will allow for continuous process improvements and more effective decision-making.

5.3 Recommendations for scalability and replication

To ensure the success of scaling and replicating the pilots, several key recommendations have been identified. First, adopting digital traceability tools, like the Plooto platform, should be a priority for improving transparency, regulatory compliance, and resource efficiency. Second, the protocols established in these pilots can be adapted to other industries and regions, provided that local factors such as material availability and regulatory conditions are considered. For instance, the CFRP requalification techniques could be applied to other composite materials, while the magnet recovery process could be extended to additional types of WEEE.

Cross-sector partnerships will be crucial for scaling these initiatives, as collaboration between suppliers, manufacturers, and recyclers is necessary for maintaining a continuous flow of materials and information. Lastly, further research and development are needed to refine processes, integrate more advanced digital tools, and explore new uses for secondary raw materials. This investment will ensure that circular economy practices are fully implemented and their benefits maximized across multiple sectors.

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