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FlexFunction2Sustain

Open Innovation Ecosystem for Sustainable Nano-functionalized Flexible Plastic and Paper Surfaces and Membranes

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= Deliverable D3.5 =

Executive summary and spec-sheets of facilities for "circularity by design", compounding and recycling and biodegradability tests

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Executive Summary

This Deliverable 3.5 (D3.5) summarizes all capabilities and performances of the "Circularity by design", compounding, recycling, and biodegradability tests facilities offered through FlexFunction2Sustain.

As with other executive summary deliverables of the project, related to Work Packages 2 & 4, this document presents the services and spec-sheets resulting from upgraded FlexFunction2Sustain pilot lines. In the case of Work Package 3 (WP3), those lines are also presented in the Deliverables 3.1, 3.2, 3.3, and 3.4, and are respectively:

- The eco-design services supported by the expertise of the OITB members for product design and the Life Cycle Assessment (LCA) tool,
- The METEOR® elongational flow mixer, for compounding services, upgraded with a cast-film line, to enable one-step recycling and converting,
- The recyclability assessment services, supported by the REMIX pilot line, upgraded with an optical sorting line and a dynamic flotation pilot-scale equipment, and aiming a Plastic Recyclers Europe's Recyclass accreditation,
- The biodegradability assessment services, supported by the BIODEGRADIX pilot line, were entirely upgraded to be accredited by TÜV Austria.

The "Circularity by Design" approach and upgraded lines enable FlexFunction2Sustain to set up strategies for the reduction of materials utilization and energy consumption, especially with the use of recycled materials in replacement of virgin materials, and the METEOR line, which is designed to consume less energy.

The present document acts as a general overview, focusing on the technical specifications of those lines, to answer the needs for the development of new sustainable nano-functionalised materials. A synthetic catalogue sums up all the WP3 lines and their specifications in the Appendix.

The diagram below summarizes the overall "Circularity by Design" approach, linking all WP3 facilities:

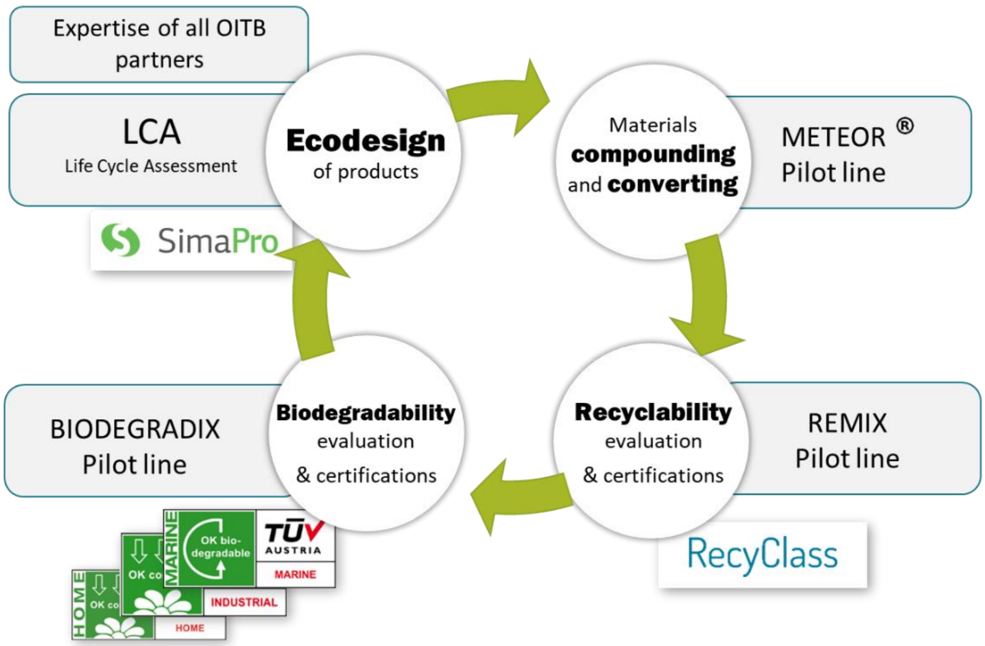

Figure 1: Sum-up diagram of the "Circularity by Design" approach

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1. Introduction

In order to support the targeted Open Innovation Test Bed (OITB) clients, Work package (WP) 3 aims at implementing a holistic Circular Economy approach to serve the customer needs for the development of innovative and more sustainable products.

This "Circularity-by-design" approach combines Life Cycle Assessment (LCA), for an eco-design of innovative products, to the manufacturing processes, such as compounding, along with the recyclability and/or biodegradability evaluations. The LCA results are used to drive the development toward more sustainable formulations (e.g. for plastic-based products), processes, and End-Of-Life scenarios, and to quantify the potential benefits of sustainable plastic products compared to traditional products. Such a combinative approach will drastically reduce the needed time-to-market for developing environmentally harmless new plastic products.

Thanks to the upgrades achieved through the first part of the project, the OITB will be able to fulfil its objectives to offer its customers the following services:

- The "Circularity by design" service, with a specific methodology for cradle-to-cradle and cradle-to-gate Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis, evaluating the different technological solutions, in relationship with the other Pilot Lines of the OITB;
- Pilot lines such as METEOR® (IPC), high shear rate mixing line (FhG-IVV), slot-die coating (FhG-IVV), thin inorganic barrier coating (AMCOR, FhG-FEP), co-extrusion (FhG-IVV) lines for the development of new formulations, and the production of new sustainable structures, for instance fulfilling the design for recyclability guidelines or bio-based and/or biodegradable;
- A pilot line, REMIX at IPC, for testing the recyclability of flexible plastic products, from the sorting stage down to the use of the recycled materials to manufacture new products, aiming for the official accreditation of Plastic Recyclers Europe - Recyclass;
- A pilot line, BIODEGRADIX at IPC, dedicated to testing the "industrial" and "home" compostability and marine degradability of plastic products, aiming for the official accreditation of TÜV Austria.

Thus, this deliverable is linked to all tasks of WP3. Tasks 3.1 and 3.2 addressed the set-up of facility cluster 5 for "Circularity by Design" services, and the detailed upgrades and achievements of the project's partners were respectively described in Deliverable 3.1 (D3.1) and 3.2 (D3.2).

Deliverable D3.1 describes the upgrades of "Circularity by design" facilities by demonstrating the processing of a 95% Polypropylene based recyclable flexible packaging material for drink pouches. Furthermore, in D3.1, the LCA methodology was presented. In D3.5, the possibilities of LCA services are disclosed, and the studies carried out for several Use Cases of the project are briefly described. The full results of those studies, however, will belong to Work Package 5.

Deliverable D3.2 describes the upgrades at the lacquering and film converting machines of FhG-IVV for the production of a PLA composite film with an oxygen transmission rate of below $0.01 cm^3/(m^2*d*bar)$, after its coating using the barrier lacquer formulation. In D3.2, the METEOR® pilot line (patented by IPC) based on elongational flow mixing technology and its upgrade was also presented. That deliverable also described its use for the development of specific material formulations with an efficient dispersion of additives while reducing the thermo-mechanical degradation of the material. In D3.5, its full specifications are summarized for a clear understanding of its possibilities.

Tasks 3.3 and 3.4 address the upgrade and verification of facilities and preparation of services for verification of recyclability and biodegradability of materials, components, and products.

Deliverables 3.3 (D3.3) and 3.4 (D3.4) will be submitted after the present deliverable, after final verification of the testing methods (e.g. TÜV Austria approval of the biodegradability testing line).

In D3.3 and D3.4, respectively, the REMIX pilot line for recyclability assessment, and the BIODEGRADIX pilot line for biodegradability assessment, will be presented with their corresponding upgrades. Those deliverables will also describe their application to FlexFunction2Sustain Use Cases. In D3.5, the different equipment composing the lines are presented, and their specifications sheets are summed up, both in a report form and in a synthetic catalogue. The recyclability and biodegradability certifications possibilities are also described.

The deliverable D3.5 is also related to WP2 and to WP4, which present the other services of FlexFunction2Sustain's OITB.

WP2 focuses on the facilities for nano-surface modification of plastic and paper surfaces to allow innovation processes from material design to market deployment. Such services are complementary to the formulation, compounding, and converting steps of the Circularity by Design approach, as they participate in the production of innovative structures, potentially recyclable or biodegradable. For instance, the R2R UV-imprinting line at JOA, initially involved in Task 3.2 for the functionalization of PLA films, will be described in D2.4.

WP4 addresses the set-up of the physicochemical and safety characterisation services, for regenerated pellets and final products, helping to confirm the recyclability of the developed structures and their industrial applicability. The facilities for Physicochemical and Functional Characterisation are thus presented in D4.1. This public catalogue of services is available at https://flexfunction2sustain.eu. Additionally, the facilities for Safety and Regulatory Compliance Testing will be presented in D4. 4.

The Annex document summarising the Circularity by Design Services will include the links to the catalogue from those other services provided by the OITB.

The "Circularity by Design" approach and upgraded lines enable FlexFunction2Sustain to set up **strategies for the reduction of materials utilization and energy consumption.**

The use of recycled materials in the replacement of virgin materials contributes to the overall reduction of materials utilization. LCA enables to compare the environmental impacts of recycled materials to their virgin equivalent or even alternative materials, to check which solution is the most desirable. FlexFunction2Sustain lines for formulation, compounding, and conversion are able to process & optimize the use of recycled materials, to ensure their properties reach the best possible values.

Energy consumption reduction is ensured by the specific design of METEOR elongational flow mixer: since this process is not based on classical extrusion, involving shearing forces, the energy it consumes is expected to be lower. Such assumption can be directly verified by specific energy consumption measurement equipment, available within the OITB. LCA again can then help identify the best scenario between several solutions involving various processes.

The present document will be publicly available, as the executive summary of all the capabilities and performances of the "Circularity by design" Facility offered through FlexFunction2Sustain.

2. Results and discussion

2.1. Circularity by Design services

2.1.1. Supported by partner's expertise & according to legislation

The development towards more sustainable solutions for plastic and paper surfaces and membranes is supported by the expertise of FlexFunction2Sustain partners.

The OITB members FhG-IVV, AMCOR, FhG-FEP, and IPC have the expertise on how to design recyclable mono-material based materials, for packaging for instance, depending on the final product requirements, and this expertise is available for the industry. The upgraded pilot lines (high shear rate mixing unit, slot-die coating, R2R UV imprinting pilot line, extrusion line, e-beam inorganic layer deposition line, …) at the consortium partners will enable to design and produce recyclable products.

As an example, innovative packaging materials can be designed to be completely recyclable. This can be achieved by using just one major basic polyolefin polymer type while maintaining functionality (e.g. adequate food-protection and prevention of food waste) with approved positive packaging tests for damage resistance, sealability, machinability, gas, and water vapor barrier, and adequate shelf life analysis with selected targeted food types. Consumer request Key Performance Indicators (KPIs) can also be tested at standard level including checks of print quality, package gloss, thickness, modulus, and sealability.

2.1.2. Supported by Life Cycle Assessment (LCA)

As presented in Deliverable 3.1, LCA is a quantitative tool used to identify, characterise and analyse the environmental impacts that a product or a system generates throughout its life cycle.

To briefly sum up and remind the methodology, the main steps of an LCA (Figure 2) are:

- **The goal and scope definition of the studied product or system**; in this phase, the application and type of LCA are described; the product or system is defined, as well as the geographical and temporal scope. This step also includes the definition of the functional unit, which acts as the reference for the subsequent steps.
- **The inventory analysis;** this second phase is the most time-consuming part of an LCA. It consists of collecting and compiling input and output data from all raw materials and processes in the studied product.
- **The impact assessment**; this step consists in evaluating the environmental impact of the inputs and outputs identified in the previous phase, translating them into environmental impacts and potential damages. This step is generally performed using LCA software.
- **The interpretation;** this step aims at analysing the results, at each step of the LCA, in order to establish conclusions transparently and always in relation to the set scope. The limits of the study must be explicit and clear. The principle of this phase is to identify the most significant processes of the assessment in order to establish priorities for action.

The process is iterative: all steps might be revisited to accommodate eventual changes in study goals and data availability.

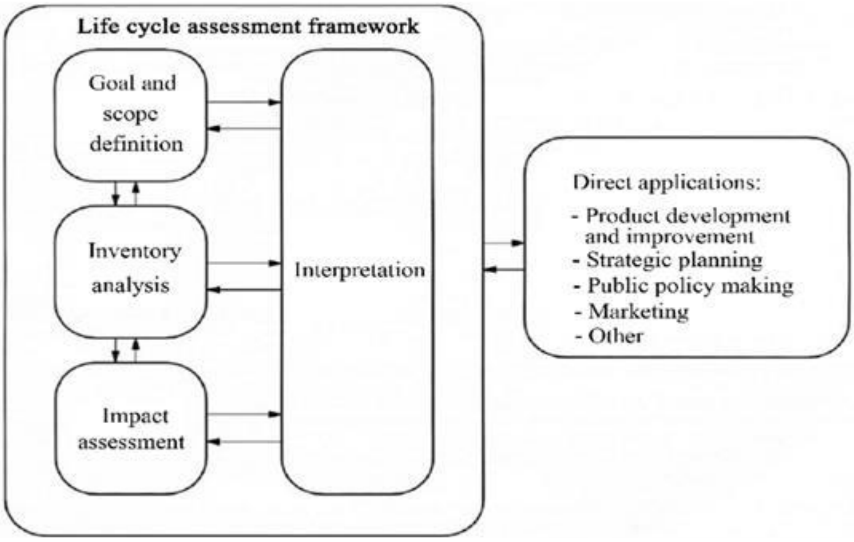

Figure 2: LCA Framework, according to ISO 14040:2006

The results of an LCA can then be directly exploited to guide the development towards more sustainable solutions, quantify the potential benefits of products compared to traditional or state-of-the-art products, and help future suppliers and clients to make more informed decisions.

To provide those services to the OITB's customers, first, the goal and scope definition step is discussed together with the client and relevant OITB members. Among other aspects, this enables the selection of the type of LCA, as a function of the lessons to be learned.

The several types of possible LCA are the following:

- **Cradle-to-grave LCA** is an assessment of the full life cycle from resource extraction ('cradle') to the use phase and disposal phase ('grave').
- **Cradle-to-cradle LCA** is a specific kind of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process.
- **Cradle-to-gate LCA** is an assessment of a partial product life cycle from resource extraction ('cradle') to the factory gate (i.e., before it is transported to the consumer). The use phase and disposal phase of the product are omitted in this case.
- **Gate-to-gate LCA** is a partial LCA looking at only one value-added process in the entire production chain.

Based on the chosen format, a **screening LCA** can then be performed, providing an overview of the major impacts of the different phases of the product life cycle and evaluating the overall environmental footprint. Screening is used to identify opportunities for environmental impact reduction within the value chain, and also serves to obtain environmental knowledge about a product and thus support eco-design. The most relevant aspects of the product design can be then studied for improvement. Several products can also be compared within the same LCA in order to identify the solution with the most virtuous environmental impact. LCA screenings are also used for internal communication, and for sharing environmental information with business partners.

For a more detailed and descriptive study, **in-depth LCA studies** can be performed, aiming for a comprehensive and complete analysis of the product under study. Most of the time, this type of LCA complies with ISO 14040/44 standards and may include a third party review and verification.

IPC uses several tools to carry out the inventory analysis and impact assessment steps. For the inventory analysis, IPC developed specific **Life Cycle Inventory sheets** to be shared and filled with the customer and involved members of the OITB. This document greatly simplifies this data collection step and helps build the assessed product's process flow, in order to consider all the required inputs and outputs.

Then, the **SimaPro software** is used in association with the **Ecoinvent 3.0 database**. This software enables the implementation of the previously gathered data, while the database provides the impact of numerous raw materials and standard processes. The product's process flow is here modelled, based on all available and approximated data.

For missing energy consumption data, for instance, for processes under development, **complementary energy consumption measurements** can be performed with **GulPlug equipment**, as displayed in the next Figure.

Figure 3: GulPlug equipment for energy consumption measurements

Depending on the considered process, and its technology readiness level and scale, such energy measurements might not be fully representative of their industrial scale equivalent, but they can give a first approach, or provide elements of comparison between alternative processes.

The software enables the impact assessment by analysing the technical and environmental inputs according to the **Product Environmental Footprint (PEF)** method, developed and recognized by the European Commission. This method defines the main environmental impacts to be considered.

This interpretation step can then be carried out by our LCA experts. They use the SimaPro software to generate and study several visualisation tools (impact indicators bar charts, lifecycle overview, and more), as illustrated in the following Figures.

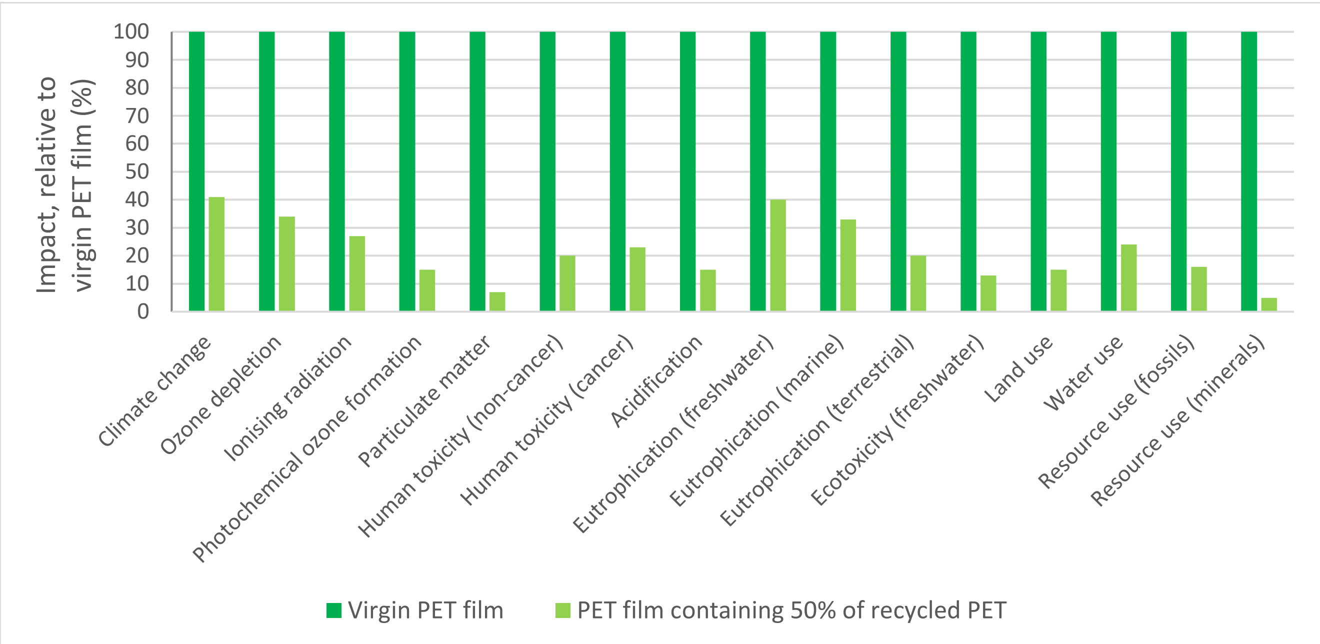

Figure 4: Impact indicators for the cradle to gate LCA of a virgin PET film vs. a PET film containing 50% of recycled PET

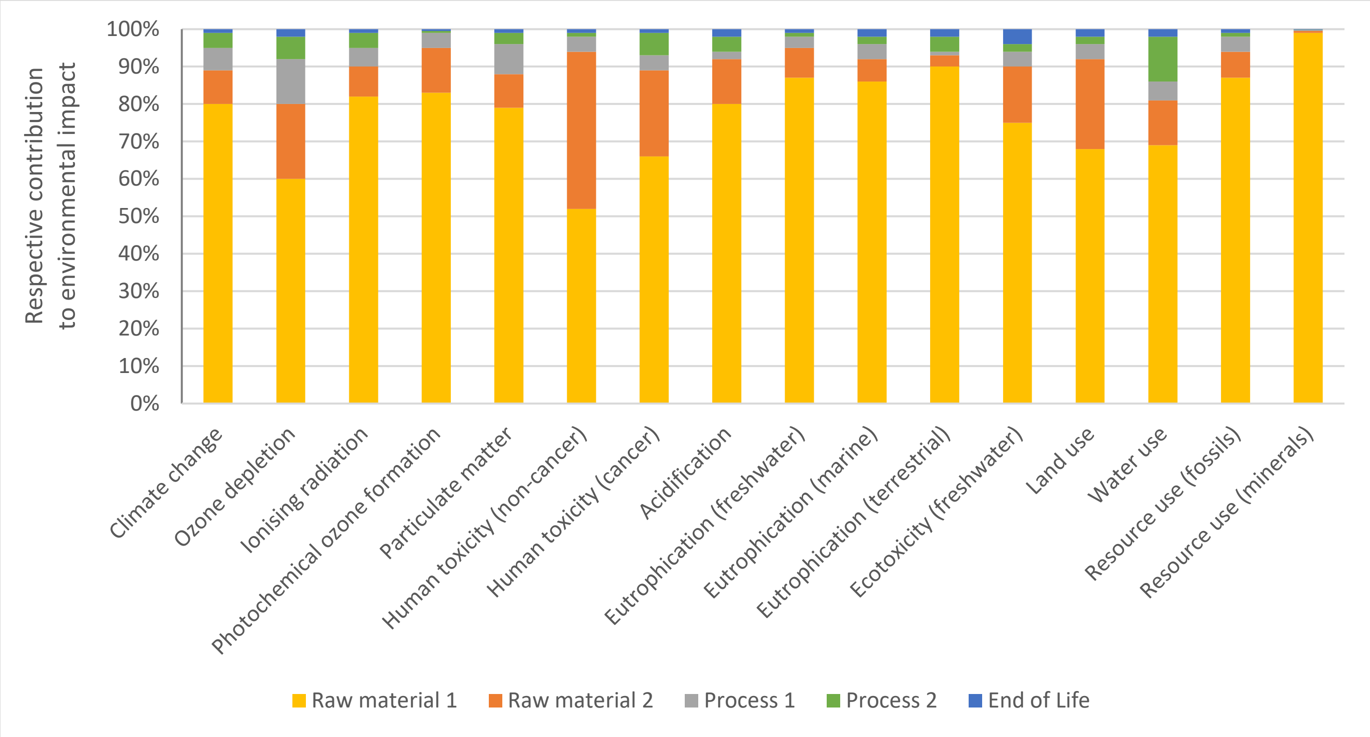

Figure 5: Product phase impacts summed per impact indicators for a cradle-to-cradle LCA

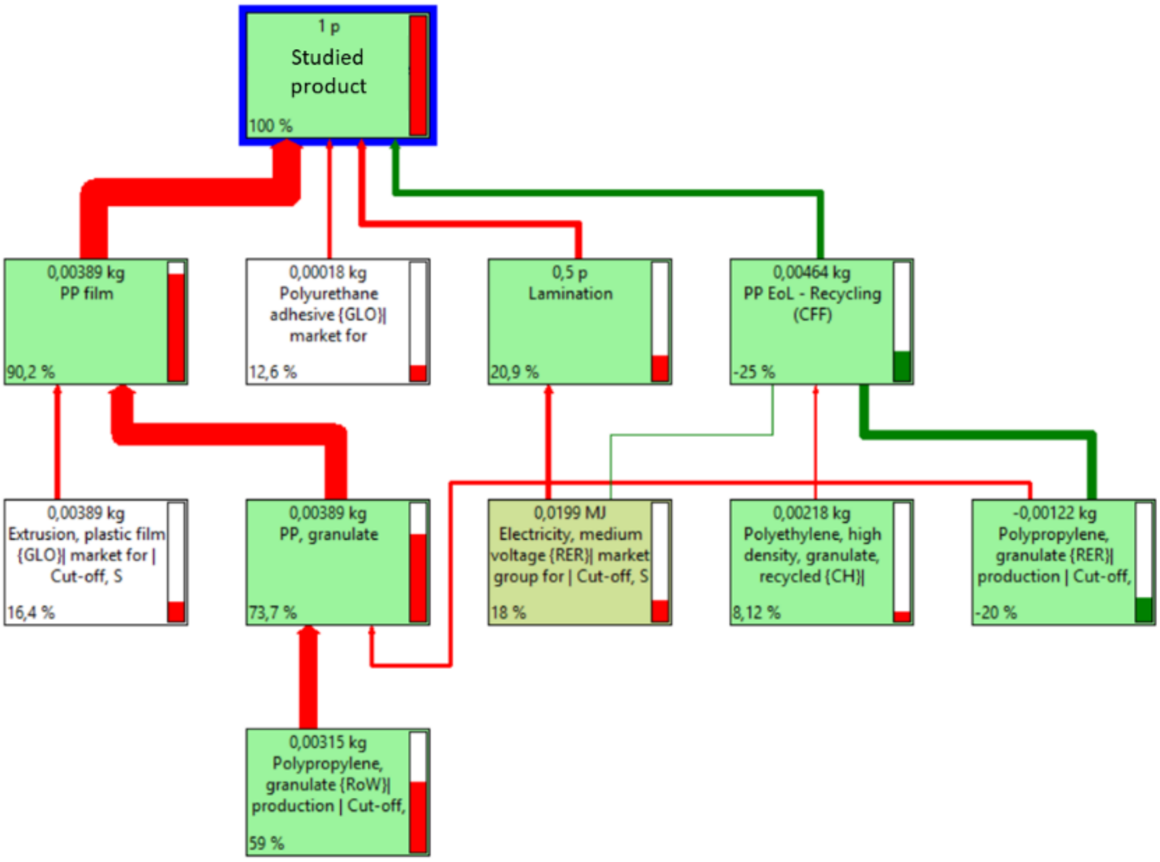

Figure 6: Lifecycle overview for the cradle-to-cradle LCA of a product displays the respective contributions of the different elements of the lifecycle (processes, materials, transportation…) to the overall impact. The red and green connectors stand respectively for negative and positive contributions.

Depending on the case, **sensitivity analyses** can be performed to test the robustness of the study. It consists of observing the variations occurring when different sensitive parameters are modified (in percentage, set maximum and minimum limits, by choice of hypotheses). Sensitivity analysis can be applied to different elements such as the functional unit, study assumptions (transportation, uncertain data, end-of-life scenario), study boundaries, allocation, data, and method choice.

An optional last step is the **Critical Review**. It is required for using the LCA results to communicate the environmental profile of a product. A critical review is a process to verify whether a Life Cycle Assessment has met the requirements for methodology, data, interpretation, and communication and whether it is consistent with the principles of the methodology as indicated by the applicable standards.

A critical review may be performed by an internal/external expert or by a stakeholder committee. The review statement, the expert's comments, and any responses to the expert's recommendations should be included in the LCA report.

Complementary to LCA, **Life Cycle Cost assessment (LCC)** is another type of study that focuses on the overall budgetary considerations involved through the life cycle of a product or a system.

To illustrate the services provided by LCA within the project FlexFunction2Sustain, the environmental performance of some of the developed products was assessed. LCA studies were performed for three Use Cases. The full results of those studies, however, will belong to Work Package 5.

For Hueck Folien Use Case, a comparative LCA between non-recyclable, recyclable, and biodegradable structures is performed. It is a cradle-to-cradle LCA study, focusing on mechanical recycling vs. compostability end of life scenario. This study enabled IPC to compare the current PET-based product vs. a recyclable product (based on recycled PET (rPET)) vs. a biodegradable product (based on PLA). IPC provided data questionnaires and started the modelling of Hueck Folien products' life cycle. The results will help Hueck Folien identify which components or manufacturing processes are the most impactful, and which alternative solution is preferable to improve their products' overall environmental impact.

For the i3Membrane Use Case, a comparative LCA to identify the best End of Life scenario for an innovative water filter membrane product was performed. It first started as a cradle-to-gate LCA study, to assess the overall impacts of i3M product manufacturing. From the preliminary results, the most impactful component or manufacturing process was identified and led to a second step, a cradle-to-cradle LCA, comparing the different possible ends of life (Incineration vs. Mechanical recycling (after products disinfection by autoclaving)). In combination with experimental tests on the REMIX line (presented later in this document, part 2.3), direct data collection was possible. The final results will help i3Membrane identify the key aspects governing the eco-design of their product, taking into account a possible valorisation of their product after its use phase.

For Capri-Sun Use Case, a comparative LCA between commercial reference and 3 monomaterial structures was performed to identify which replacement solution is the more environmentally friendly. It is a cradle-to-cradle LCA study to compare the current non-recyclable multimaterial structure to the three recyclable monomaterial structures developed within FlexFunction2Sustain. The results will help Capri-Sun identify the most sustainable alternative to its current product, and maybe further improve its product's eco-design by focusing on the most relevant components or manufacturing processes that could be optimized.

Those application examples concretely show how LCA can support the eco-design of innovative products.

FlexFunction2Sustain offers those services as a result of its partners' expertise development, to assist with the guidelines on how to develop more sustainable products. We are now fully equipped to successfully support clients willing to assess the environmental impact of their product, to lead an eco-design approach, or before placing them on the European market.

2.2. Processing facility: METEOR® Pilot Line

METEOR® Pilot line (patented by IPC, Figure 7) is based on an innovative extensional flow mixing technology used to develop specific material formulations with an efficient dispersion of additives while reducing the thermo-mechanical degradation of the material.

This pilot line is dedicated:

- to reach good dispersive and distributive mixing, the two key conditions for a successful plastics compounding;
- to reduce the shearing forces, compared to the traditional extrusion machine like the twin-screw extruder;
- to reduce the shear heating (also called the overheating of the polymer melt) which will avoid the thermal degradation of the polymer melt (for sensitive polymers like biobased polymers);
- to reduce indeed the power consumption during the compounding process.

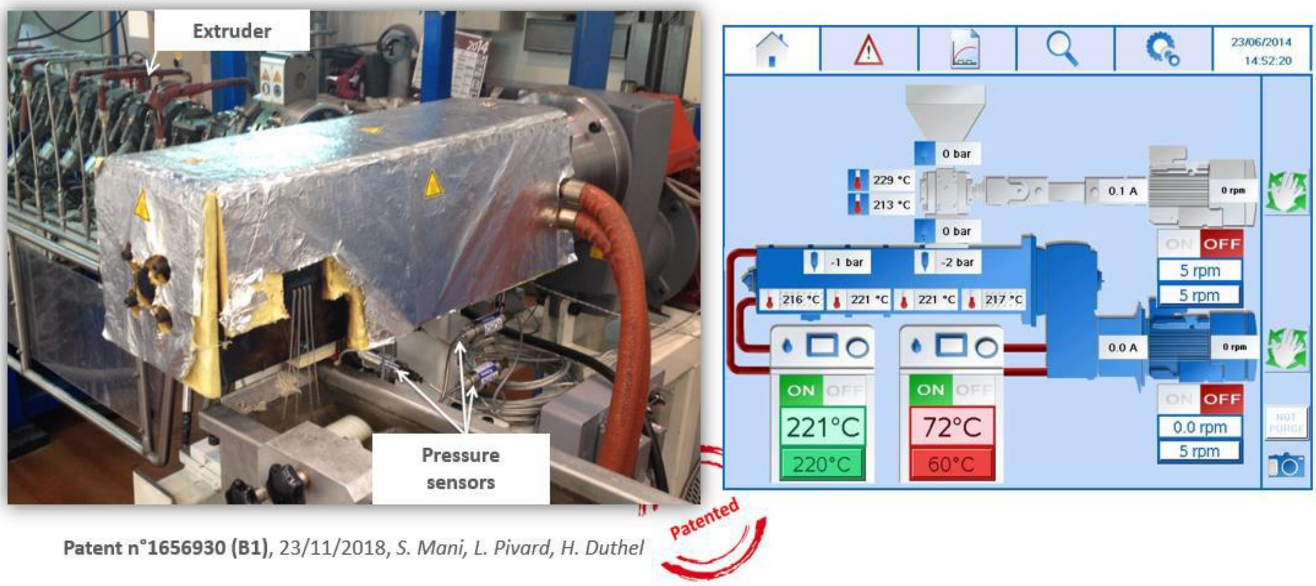

Figure 7: The continuous extensional flow mixer METEOR®

The used Continuous Extensional Flow Mixer METEOR® is based on:

- an original design of screw and barrel to provide a strong extensional strain and a continuous division and then recombination of the polymer melt flow: to reach a high quality of dispersive and distributive mixing;
- a modular screw and barrel design that offers wider flexibility for compounding and recycling;
- real-time supervision and exploration of the process data;

With this machine, we can work at high temperatures, up to 350°C, and at throughput rates from just a few kg/h up to 100 kg/h.

Based on the patented mixing technology METEOR®, IPC has implemented a new process that could bring together all the benefits of recycling and successful plastics material compounding in one process (Figure 8):

1) The ground or shredded plastic wastes are automatically fed into a single or twin-screw extruder. In the extruder screw, the material is plasticized, homogenized, and then cleaned in a filter system;

2) The prepared and cleaned melt then goes via a melt pump directly to the METEOR® extensional mixer. The role of the melt pump is to provide, a stable throughput by smoothing out, the fluctuation generated by the dosing device due to the irregular shape of the ground plastic waste;

3) With its excellent mixing and gas removal properties, at a very low shearing rate, to avoid the thermal degradation of the molten, this flexible part of the system can handle all compounding tasks. Besides the dosing of a wide variety of additives with a wide range of viscosity, high amounts of fillers and reinforcing agents can be admixed.

4) Then, in the gas removal zone, the compounded melt is degassed and moves to a pelletizing system.

The process described above corresponds to the production of pellets. It is also possible to add a flat die, at METEOR® output, for film extrusion. That is what was implemented to upgrade the METEOR® pilot line.

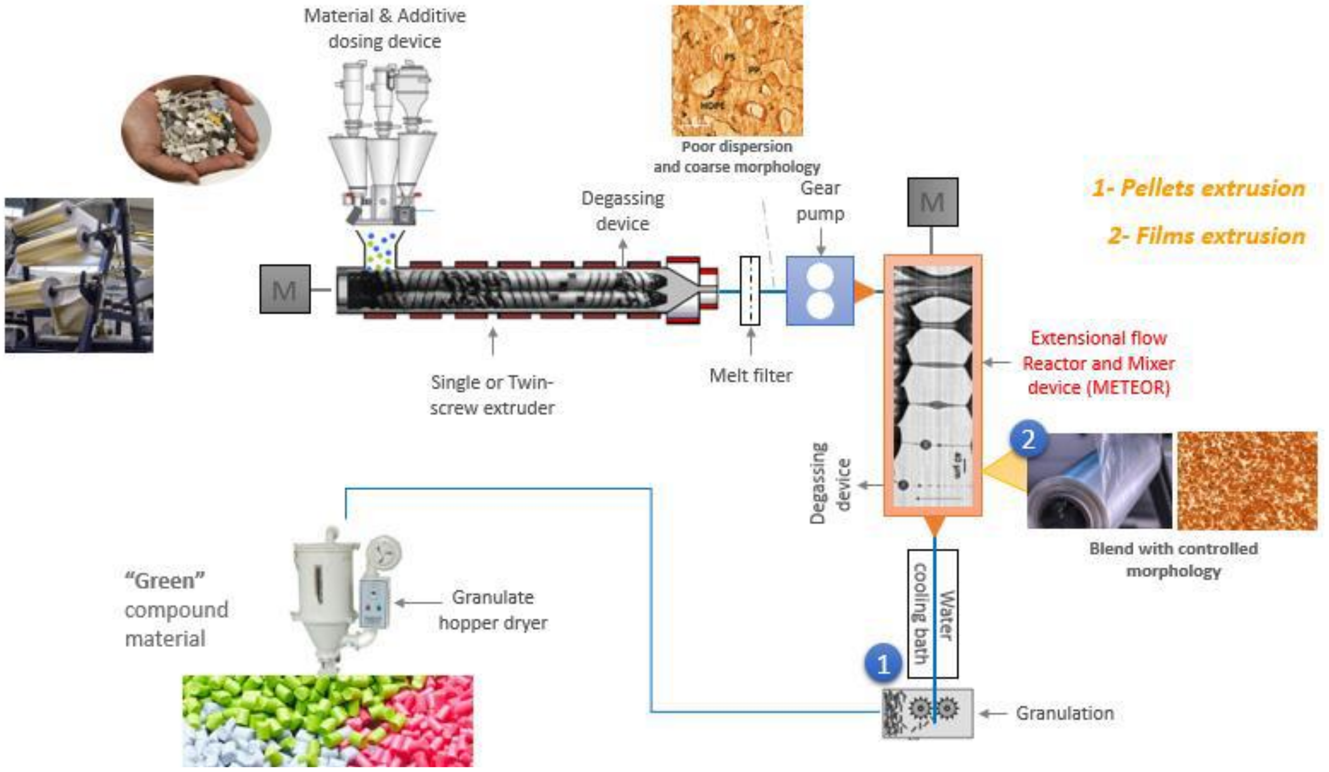

Figure 8: The METEOR® Pilot line for compounding and recycling in one step

METEOR® Pilot line Up-grading:

Biobased polymers are often sensitive and tend to degrade at high temperatures during the extrusion process. Today, overheating could be above 50°C from the set temperature, based on standard extrusion machines.

Indeed, the thermal stability of these polymers has to be improved by upgrading the extrusion and compounding process as well as identification of the dedicated biobased polymers and/or additives.

The mostly used biobased and thermosensitive polymer is PLA. PLA exhibits high oxygen and water vapour permeability.

The applications for such extruded films are targeted for sealing films, packaging lids (at PLA layer thicknesses of 50 to 100 µm), or thermoformable trays (at a PLA layer thickness of 300 µm).

Therefore, IPC has upgraded its METEOR® Pilot line in order to:

(1) Develop specific material formulations with controlled morphology and efficient dispersion of polymer phases and/or additives for bio-degradable and polyolefin-based polymers;

(2) Reducing or avoiding the overheating and the thermomechanical degradation during the compounding, extrusion, and recycling process. For this, an inline rheometer has been selected in order to control the melt flow evolution during processing trials;

(3) Implement co-extrusion, flat die, and film take-off station to produce films of 25 to 250 µm in thickness and 300-330mm in width. This equipment was installed and used to prepare the samples presented in the deliverable D3.2.

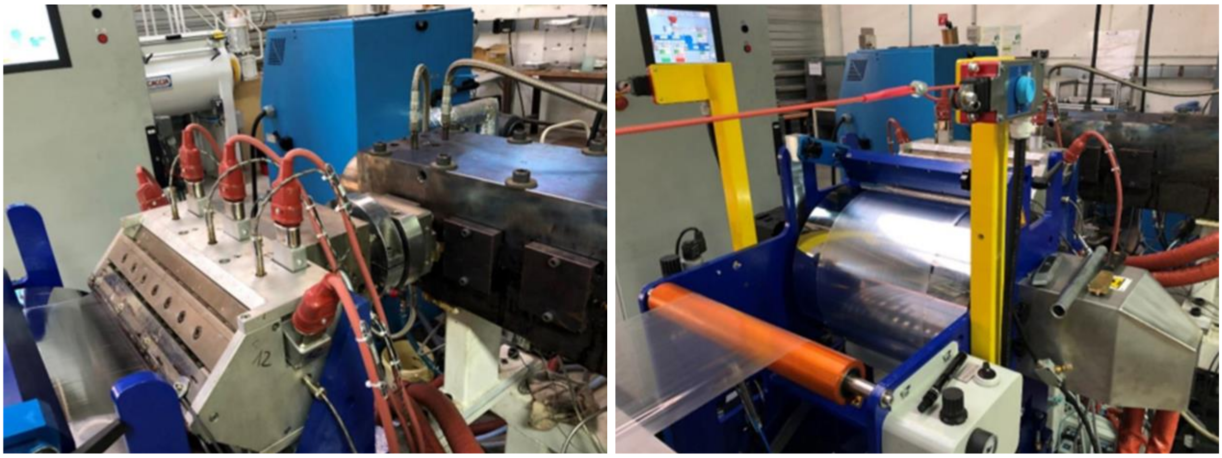

Figure 9: METEOR® equipped with the flat die (left) and film take-off station (right)

FlexFunction2Sustain offers those compounding & converting services, tailored for recycling and/or thermally sensitive materials, as a result of the METEOR® pilot line upgrading. We are now fully equipped to successfully support clients willing to develop innovative structures with advanced equipment optimized to answer their specific processing needs.

2.3. Recyclability assessment facility: REMIX pilot line

The REMIX Pilot line is dedicated to product recyclability tests and allows to work at a semi-industrial scale, exploring the technical and economic balance between recovery in the pure streams and mixed ones, with a special focus on mechanical recycling.

The recyclability of the new materials developed in the frame of the OITB can be demonstrated following the conditions defined by Plastic Recyclers Europe [1]:

Compatibility with existing sorting technologies can be assessed at a pilot scale with a Near-Infrared optical sorting (NIR) machine and a semi-automated high volume-specific sink-float technology dedicated to films.

Regeneration of products and materials can be evaluated on the REMIX Pilot Line. After shredding, washing, and drying along with state-of-the-art industrial protocols, the plastic fluff can be filtered and regenerated through a twin-screw extruder and transformed into standard pellets.

Reprocessing the recycled materials into new products can be validated using the pellets obtained after the regeneration through their re-processability via cast-film extrusion, injection moulding, extrusion of tubes, and extrusion blowing of films.

Lastly, **physico-chemical characterisation** of the regenerated pellets and the final products allows for confirming the recyclability of the developed structures.

The recyclability evaluations are conducted so that the recyclability testing protocols published by the Plastics Recycler Europe for Technology Approval are fully applicable using the REMIX pilot line. IPC applied for official accreditation of the REMIX pilot line by Plastics Recyclers Europe, and it is already recognized as a Certification Body regarding the Recyclability Certifications delivered by auditors.

The REMIX pilot line's main steps for the assessment of recyclability are:

- **Sorting,** with a near-infrared optical sorting machine;
- **Pre-treatments**, including grinding, washing, flotation, and drying steps;
- **Extrusion**, successively with a thermogranulator, dedicated to converting the shredded film flakes into densified flakes into an agglomerated form, then with an extruder equipped with a filter, to allow a molten state filtration and remove impurities;
- **Converting** back into films, with a cast-film extrusion line.

2.3.1. Sorting

Near-Infrared Optical sorting

The REMIX pilot line has been upgraded with the installation of a Mistral + Connect Near Infrared Optical sorting machine (Pellenc ST), as seen in Figure 10. This machine was selected to be representative of modern sorting centers while offering the versatility to perform several types of testing.

Equipped with a multi-stream spectrometer, its detection covers near-infrared to visible spectra. A sample will be detected from its visible upper surface material by analysis of the reflected spectra within the covered wavelengths. Thus, any sample reflecting light within the near infra-red to visible spectra can be analysed and recognized.

Linked remotely to Pellenc ST database, including most polymers, the machine settings can be adjusted to sort by air-jet blowing one or several detected materials. It counts two exits: one for the ejected fraction, i.e. the sorted fraction, and the other for the rejected fraction.

Figure 10: Mistral + Connect Near Infrared Optical sorting (Pellenc ST)

Static detection tests can be performed to assess if a structure under development is detectable by the machine. Upon success, such a structure can be evaluated in its final form through dynamic tests. These dynamic tests can occur either with several units of the sample alone or within a waste stream to mimic their behaviour in a real-life situation.

Several steps can then be studied. The first optical sorting step in a sorting center occurs on a mix of plastic packaging, paper/cardboard, and aluminum wastes. Later on, plastic wastes are sorted amongst each other through an optical sorting step to isolate each stream regarding its composition (PET, PP, PE…).

The main key results of dynamic tests are the efficiency of the stream sorting and the purity of the sorted stream. The efficiency measures the ability to gather the entire aimed stream, while the purity covers the ability to gather specifically the aimed stream.

This machine can be fed with either flexible or rigid samples, smaller than 350 mm and with an area density up to 10 kg/m², and is equipped with a high-resolution sorting bar to enable the sorting of smaller elements down to 20 mm.

Detection of widely used petroleum-based plastic (PET, PP, PE…) is possible, as well as the detection of biopolymers. The exceptions to the machine's detection and sorting abilities are non-exhaustively summed up in the next Table.

Table 1: Main exceptions to the Mistral + Connect detection and sorting abilities

Plastic films with a thickness below 15 µm
Black and very dark objects
Materials containing carbon black
Objects constituted of different inseparable materials (including multilayers, such as PE/cardboard)
Rolling objects
Packaging containing more than 100 mL of liquid
Synthetic textiles (polyesters…) cannot be sorted from a plastic stream
Natural fibers textiles cannot be sorted from a wood, paper and cardboard stream
Wet paper, cardboard, wood & natural fibers textiles are detected as the same material
PVC containing less than 20% chlorine
Inorganic chlorine (salts)

An original design of conveying systems has been implemented by IPC, with the objective to set up an optical sorting line representative of the state of the art sorting facilities. This upgrade of IPC's optical sorting line allows sorting in a loop, either to enable refined sorting, with the same stream being purified through each pass, or to simulate a cascade of several NIR sorting machines, each pass sorting a different stream. Therefore, several conveyors form a loop (Figure 11) around the machine.

Sorting tests can follow different protocols, depending on the needs. For example, Recyclass (European) [2] or COTREP (French) [3] protocols regarding optical sorting of packaging could be performed. The base principle of those protocols is to test a known number of packaging units – typically 50 to 100 units, depending on their size - within a waste stream

Briefly, depending on the samples to be assessed, their optical sortability can be tested: by static testing, to screen the most detectable structures, and/or dynamic testing, either alone, within a sampled or model stream waste, and/or with a refined sorting by looping through the optical sorting machine for several passes.

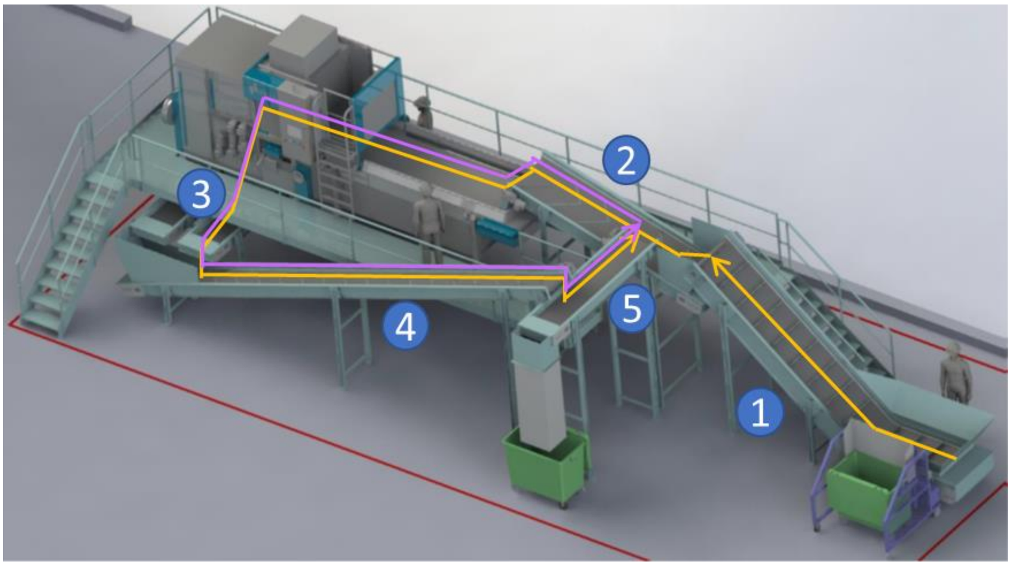

Figure 11: Conveyors loop around the sorting machine

2.3.2. Pretreatments

The recyclability evaluation for a Technology Approval of an innovative product starts at this point. The steps and equipment are described below.

Grinding

The grinding is performed by a **single shaft shredder** (Figure 12). The equipment consists of a shaft with a dozen moving cutting tools and various calibrated grids of 10, 20, and 30 mm.

The shredder is equipped with a vacuum emptying system; its flow rate varies depending on the shape and material of the products to be processed.

Figure 12: Shredder

Washing step

The washing is carried out in a **washing module** equipment (Figure 13) with a temperature-regulated tank where the sample is washed by friction under the effect of a rotating agitator and a set of fixed blades.

Then, the tank is unloaded onto a vibrating screen to collect as much water as possible that can be reused for a new wash. To finish, the washed wastes are conveyed by an endless screw to a dryer before being evacuated by a cyclone.

Figure 13: Washing module (left: dryer & cyclone, right: washing tank)

Wet sorting

Sink and float sorting are used extensively at the industrial level. Our pilot line was upgraded with a **dynamic flotation bath** (Figure 14), equipped with several rollers on the water surface, conveying the materials through the vessel. Regular feeding over the entire width of the vessel is provided by a vibrating conveyor and a spray bar. All flakes are immersed several times before being evacuated by overflow for the floating fraction. This allows wet sorting based on density and removes contaminants and impurities like wood and metals (making it possible for less dense materials to float and the heavier ones to sink).

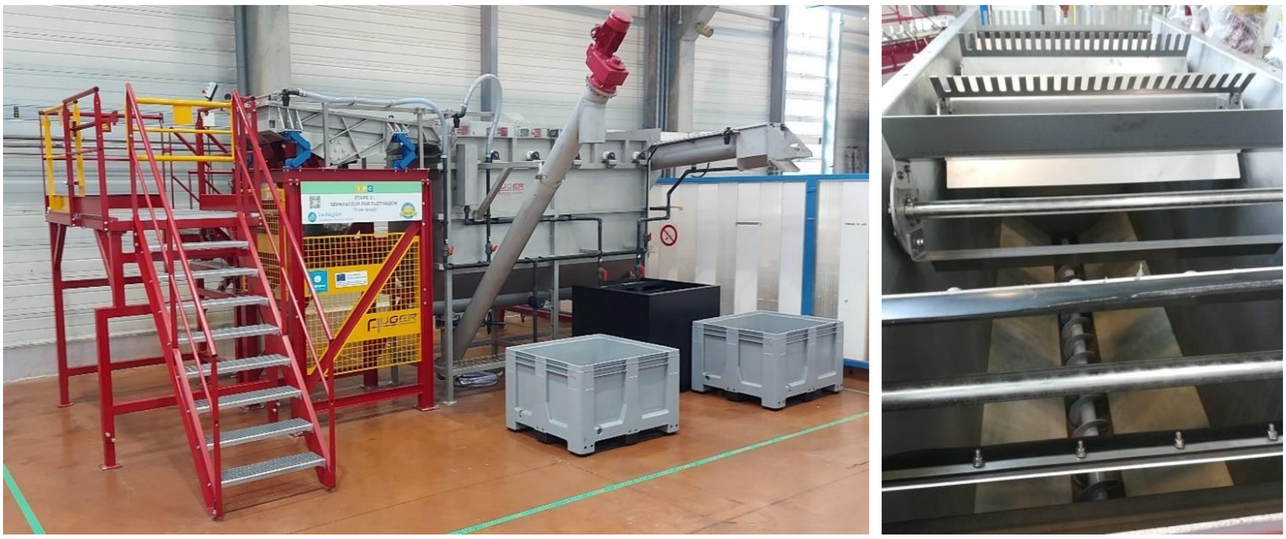

Figure 14: Dynamic flotation bath (left: outside view, right: inside view)

Drying

Drying steps are carried out in an **industrial oven** (Figure 15). If necessary, the drying is performed by a flow of heated air distributed over the entire surface of the oven for uniform drying. The films to be dried are packaged in fabric bags allowing handling and avoiding cross-pollutions

Figure 15: Industrial oven (left: outside view, right: with fabric bags)

2.3.3. Extrusion

After the pretreatments, the sorted, ground, washed, and dried samples go through the mechanical recycling step of filtering and compounding. Beforehand, if the samples are shredded film flakes, they need to be transformed into an agglomerated form through densification.

Film densification

The **thermogranulator** (Figure 16) has the particularity of being able to transform plastic films from a shredded form to an agglomerated form; its feeding system is composed of an auxiliary screw making it possible to feed the plasticizing single screw with a large volume of raw material.

The thermogranulator is used to densify the ground films to make them usable in standard processing techniques in the plastics industry.

Figure 16: Thermogranulator

Melt filtration

The **corotating twin-screw extruder** is characterized by a screw diameter of 32 mm and an L/D ratio of 44.

The raw material supply is ensured by a set of weight feeders allowing the dosing of a multitude of solid and liquid materials.

Filtration of the molten material is carried out by a manual two-position **filtering system** (Maag HSC-050) located at the head of the extruder (Figure 17). The filtration diameter is 50 mm, i.e. the filtration surface is approximately 20 cm^2, a pressure sensor placed before the screen allows monitoring clogging of the filter. This filtration system can work at a differential pressure of around 200 bars and temperature up to 300°C. The filtration fineness can be adjusted through different filters and filter combinations: 105 µm, 150 µm, 300 µm, and 500 µm.

The extruder is equipped with a water cooling tank to solidify strands, which are then cut into cylindrical granules in a granulator.

Figure 17: Extruder and melt filter

2.3.4. Converting

The processability and conversion of the recycled material into the new plastic part can be tested and optimized at the pilot scale. IPC is equipped with a wide range of converting machines, including dosing, mixing, compounding, filtering, profile, and tube extrusion, calendaring, co-extrusion, blown film extrusion as well as injection moulding machines. For the regeneration of films, in particular, the same extrusion cast-line mentioned in part 2.2 can be used, directly associated with an extruder.

Cast film extrusion

The **cast film line** is equipped with a 350 mm wide flat die, the adjustable lips of which allow the thickness to be varied from 25 to 250 µm.

The die head is equipped with ten heating zones (eight control zones distributed over the entire flat die and two heating zones for the upper and lower lips) adjustable up to a maximum temperature of 300 °C.

The pulling line is made up of a temperature-regulated 400 mm diameter chill-roll; the temperature of the roller can be controlled between 40 and 160 °C with oil (Figure 18).

The rotational speed of the chill-roll allows the film to be stretched over a range of 0 to 35 m/min. Four steel rollers are arranged along the line to allow air-cooling of the film. Finally, a movable roller at the end of the line not only keeps the film tension constant but also rolls up the film obtained. A cutting module allowing a “slackening” operation can be placed upstream of this roll.

Figure 18: Cast-film line

2.3.5. Characterizations

Laboratory tests are performed to assess the quality of recovered plastics after the mechanical recycling. Table 2 sums up, non-exhaustively, the equipment available to perform the necessary analysis.

Table 2: List of the analysis & laboratory equipment involved in recyclability assessment

Analysis	Equipment
Bulk Density (ISO 15344)	- Apparatus for the determination of bulk density - 2000 ml.
Density (ISO 1183-1)	- Precision scale METTLER TOLEDO AE240; - Accessories for density measurement.
M**elt Index (ISO 1133)**	- Melt Flow Indexer GOTTFERT Mi-40; - Capillary die, length 8 mm and diameter ≈ 2.1 mm; - Precision scale METTLER TOLEDO AE200; - Ventilated oven HERAEUS UT 6060.
Ash content (ISO 3451-1)	- Muffle furnace NABERTHERM; - Precision scale METTLER TOLEDO AE200
DSC (ISO 11357-3)	- DSC calorimeter Q100 TA Instruments ; - Indium reference standard; - Lead reference standard; - Precision scale METTLER TOLEDO AE240.
Volatiles	- Ventilated oven HERAEUS UT 6060; - Precision scale METTLER TOLEDO AE200; - Timer NOVO 82110.

Colorimetry (L*,a*,b*)	- Spectro guide BYK Gardner.
Thickness (ISO 4593)	- Heidenhain thickness gauge.
Tear Strength (EN ISO 6383-1 or EN ISO 6383-2, Elmendorf method)	- Zwick/Roell BT2-FR005TH.A50
Tensile properties (ISO 527-3)	- Dynamometer ZWICK 1.0; - 1 kN sensor; - Thermo-hygrometer TESTO TERM 6010; - Digital micrometer 25 mm.
Dart Impact (ISO 7765-1)	- Dart Tester
Gels and Specks	- Microscope VHX-7100 KEYENCE.

2.3.6. Certification possibilities

The whole REMIX line presented above enables the OITB to apply the **Recyclability Evaluation Protocol for Films,** called **RecyClass protocol**, and developed by PRE (Plastics Recyclers Europe). It is a methodology that must be followed by the plastics packaging producers, at a pilot scale, in order to identify if a plastic packaging innovation is compatible with the existing post-consumer film recycling streams.

As for the previously presented recycling steps, the protocol follows three main phases, as illustrated in Figure 19: pre-treatment, extrusion, pellet characterization, and conversion, also followed by characterization. The input required at the beginning of this protocol is around 10 kg of innovation film and 25 kg of control film. The control film should be the same base resin as the innovation, except for the specific ingredient/feature being evaluated. During the extrusion step, three blends of control and innovation flakes will be prepared, containing 0%, 25%, and 50% of innovation. During the conversion step, the batches will be diluted again, with 50% of virgin pellets, in order to prepare three blends of control and innovation pellets, containing 0%, 12.5% and 25% of innovation. This protocol will be described in detail in Deliverable 3.3, applied to one of the FlexFunction2Sustain use cases.

Based on the processability and characterizations of the recyclates, the difference between the control film and the innovation film is assessed. If the innovation packaging is successfully recycled through the protocol, a Technology Approval can be delivered by Recyclass.

Complementary to this technology approval, packaging or semi-finished packaging can also be certified through Recyclass by IPC, a Recyclass-recognized Certification Body. There are three types of recyclability assessments for plastic packaging, answering the needs of the entire plastic value chain. Packaging entirely covered by the Design for Recycling guidelines can be evaluated as follows:

- **Design for Recycling Certification** classifies qualitatively from A to F the technical recyclability of a final plastic packaging on the EU market. All the recognized Certification Bodies are accredited for this assessment.
- **Recyclability Rate Certification rates** the effective recyclability of a final plastic packaging in the specific geographical area for which the assessment is conducted. IPC is able to deliver the Recyclability Rate Certification for France.
- **Letter of compatibility** evaluates the recyclability of semi-finished packaging qualitatively and based on the Design for Recycling Certification. All the recognized Certification Bodies are accredited to deliver a Letter of Compatibility.

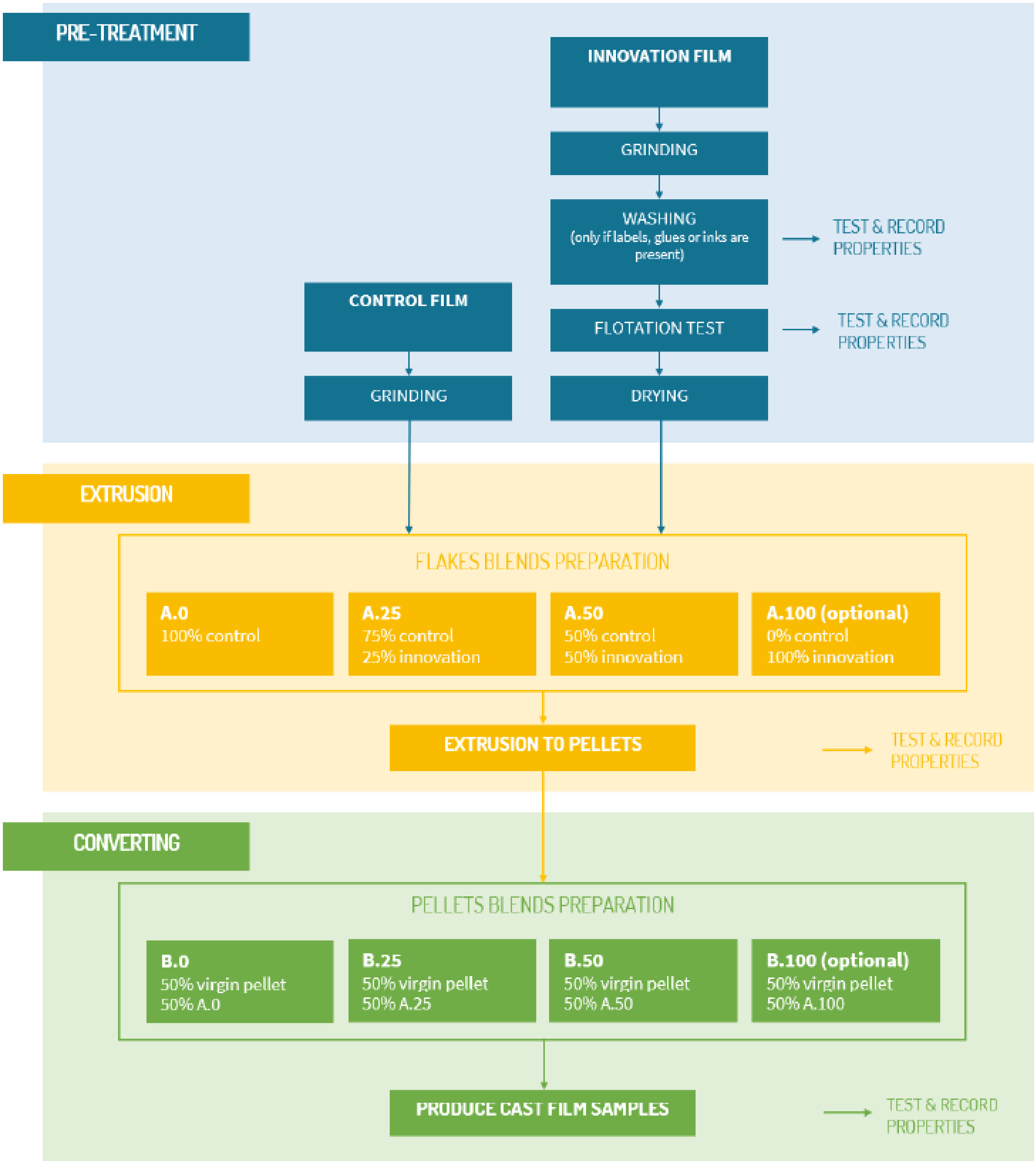

Figure 19: The Reclyclass protocol for PP flexible packaging (publicly available on Recyclass' website [4])

FlexFunction2Sustain offers those services and high-value expertise using the upgraded REMIX pilot line. We are now fully equipped to provide specific indications and recommendations to the European packaging producers for the Eco-design of new film structures that will allow the flexible packaging industry to switch from non-recyclable laminates multilayer to fully recyclable mono-material flexible packaging. The REMIX pilot line is ready to be used to support our clients in developing sustainable packaging and reduce their time-to-market.

2.4. Biodegradability assessment facility: BIODEGRADIX pilot line

The BIODEGRADIX Pilot line is dedicated to products' biodegradability assessment and enables the evaluation of a product's behaviour in various degradation conditions: **industrial compost, home compost, or marine environment.**

It must be noted that the biodegradation of a product varies from one environment to another. In most cases, it is the microbial activity and the temperature that determine the rate and level of biodegradation. Compost is considered the most aggressive environment, while landfill is considered the least aggressive environment. It is therefore not possible to extrapolate positive biodegradation results from one environment to another.

The BIODEGRADIX line will enable the FlexFunction2Sustain OITB to assess all the parameters allowing a global interpretation of the biodegradation potential of innovative material. Indeed, composting is not the principal end of life occurring for plastic and paper products. Approximately 80% of the plastic found in the sea comes from terrestrial activities. The study of plastic degradation in the marine environment is thus essential to answer the objectives of environmental impact improvement within the development of new products. The selection of proper experimental conditions can be advised and discussed before the testing, in order to answer best to the OITB customers' expectations.

The BIODEGRADIX lines different steps for the biodegradability assessment are the following:

- **Quality of the material**
- **Biodegradation** shows quantitatively the inherent characteristic of the material to be consumed by microorganisms and protects the environment by showing that the material will not accumulate in nature. Biodegradability is therefore linked to the chemical composition of a material and represents the percentage of solid organic converted to gaseous under the form of CO_2.
- **Disintegration** measures whether the material visually breaks down and falls apart. In other words, the disintegration of material is linked to its physical form and is therefore strongly affected by its thickness, grammage, and/or density.
- **Ecotoxicity testing** determines whether the waste materials left behind after disintegration show any inhibition of plant growth or the survival of fauna. Finally, heavy metals need to be quantified to assure that the material will have no negative effect on the quality of the end product (compost).

2.4.1. Quality of the material

The sample is characterized to assess its inherent chemical toxicity (heavy metals, infrared analysis, and Fluor assaying).

2.4.2. Biodegradation

IPC is equipped with **a 36-channels and two 12-channels respirometers** dedicated respectively to Industrial compost conditions, Home Compost conditions, and Marine Environment (Figure 20). These devices are designed to perform aerobic or anaerobic biodegradability tests. The respirometers measure O_2 (oxygen) and CO_2 (carbon dioxide) concentration inflow through the sample under controlled conditions.
One test in triplicate needs nine channels: three for a control environment, three for reference material, and three for the sample. Of course, several samples can be analysed in the same conditions, with the same control and reference, provided that their biodegradation evaluation is started at the same time.

Figure 20: Respirometers for biodegradability assessment, left: in compost condition, right: in marine environment

For a biodegradation evaluation, samples should be in powder form. BIODEGRADIX line includes a **shredder, cutting mill, and impact grinder**, available for the shredding, (cryo-)grinding, or milling of different types of materials, including rigid and flexible plastics. The sample's biodegradation will be compared to a reference material, typically microcrystalline cellulose; therefore, the sample powder granulometry should ideally be as close as possible to the reference for an optimized interpretation, but samples up to a 2x2 cm size can be assessed.

The sample's total organic carbon content must also be analysed to interpret the biodegradation rate.

Typically, for triplicates, 300g of powder sample is used for a compostability test, and around 1 g of powder sample is used for a biodegradability test in a marine environment.

For tests in **compost conditions**, the compost is sifted to guarantee its aeration and size of organic fragments between 0.5 and 1 cm. Its quality is characterized in terms of humidity content, volatile solids, pH, and minerals (nitrogen, phosphorus, magnesium, potassium). The compost must be active enough for its bacteria consortium to produce CO_2 and degrade at least 70% of the reference cellulose during the first weeks of the biodegradation test. The exact compost activity characterizations are specified depending on the standard to be followed.

The standards NF-EN 13432 and NF-T-51 800 apply respectively for the **industrial composting** and **home composting conditions**. These standards consider the biodegradation of the sample for up to 6 months at 58°C or up to 12 months at 25°C, respectively.

For tests in **marine environment conditions**, natural seawater is sampled shortly before the biodegradation test. The standard ASTM D6691 applies to such biodegradation tests in marine environment. It considers the biodegradation of the sample for up to 6 months at 30°C.

For all conditions, the biodegradation determination is calculated by deducting the control environment respiration from the sample respiration. The sample is considered biodegradable if it achieves 90% of the reference in due time.

2.4.3. Disintegration

Disintegration in composting conditions can be evaluated at lab-scale, according to standard ISO 20200, or at pilot-scale, according to standard ISO 16929.

This latter one is a quantitative test where the sample is mixed with bio-wastes, synthetically prepared with a known ratio of various elements – such as food rabbit, green wastes and fruits, sugar, mature compost, horse manure… - in order for the composting process to occur with a controlled temperature evolution. This test needs to be carried out with enough material so that the bacterial activity will cause a self-heating effect. IPC is thus equipped with **six thermally insulated tanks** (Figure 21), allowing for simultaneous duplicate tests for a control, reference and one sample. The disintegration test will last for up to 6 months, and its result is measured with successive sifting steps, at 10, 5 and 2 mm. The resulting compost will then be used to assess the ecotoxicity of the degraded sample (see 2.4.4).

Figure 21: Thermally insulated tank for self-heating disintegration in composting conditions (pilot-scale)

Since the previous test requires several kilograms of samples, a **smaller scale disintegration test** can also be performed, when a further ecotoxicity test is not considered. This test is led on **reversal film frames** (Figure 22), placed with biowastes in **reactors with a controlled temperature and humidity**. The samples' appearance is observed every week and quantified at the end of the process, lasting up to 6 months.

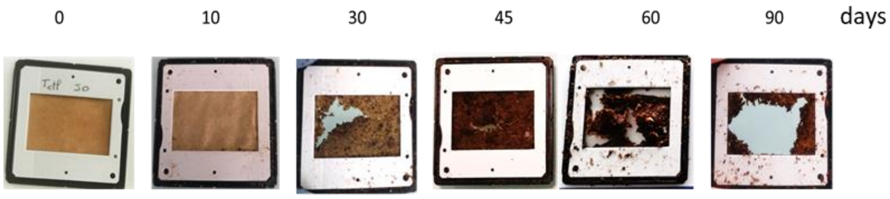

Figure 22: Reversal film frames used for a lab-scale disintegration test in composting conditions.

For the **disintegration test in a marine environment**, the same parameters as the ASTM D6691 standard are followed. The disintegration is tested in natural seawater at 30°C, under stirring, for a maximal duration of 84 days, when 90% of the tested sample should be disintegrated (Figure 23).

Figure 23: Ongoing disintegration test in marine environment

2.4.4. Ecotoxicity

The ecotoxicity of tested samples is evaluated on the living organisms relevant to the considered environment.

For **composting conditions**, this test is made on the products of degradation from the previous test (2.4.3). The impact of the pilot-scale compost containing the disintegration products issued from the sample is assessed on two plants, **wheat and white mustard**. The germination and growth rates of those plants are compared for a known number of seedlings in the evaluated compost (initially containing the sample) and in the control compost. This test is compliant with the standard OCDE 208. According to it, at least 90% of plants should sprout and grow compared to the control group (Figure 24).

Figure 24: Seedlings and growing plants for the compost ecotoxicity evaluation

For the **marine environment**, according to the standard OCDE 202, ecotoxicity is tested on micro-zooplanktons (Daphnia Magna), which actually live in freshwater (Figure 25). The samples are previously disintegrated in sludge water, and its disintegration products should have no toxic effect on those aquatic organisms, with a survival rate of at least 90%.

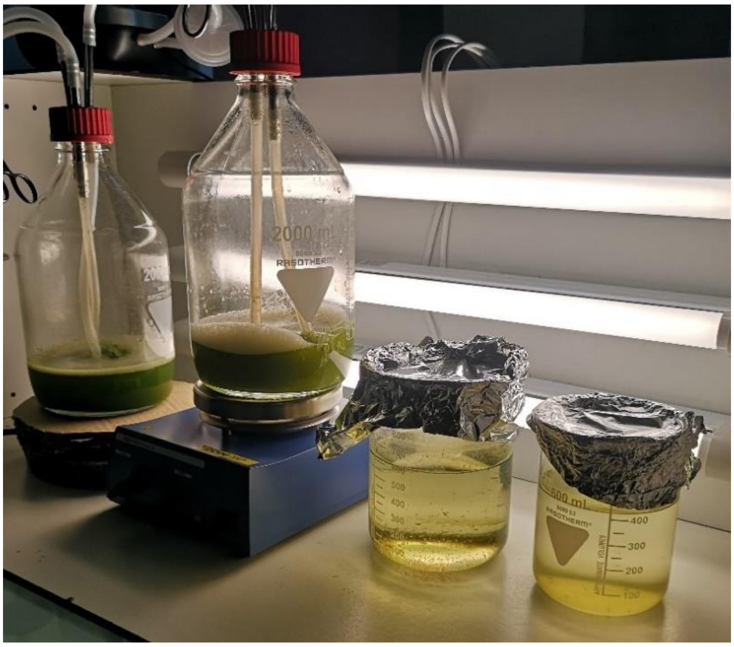

Figure 25: Daphnia magna culture for ecotoxicity evaluation in aquatic environment

2.4.5. Certification possibilities

IPC will apply to obtain an official accreditation from TÜV Austria, which is the European reference regarding the delivery of the biodegradable and compostable labels for plastics.

The OITB should then be able to deliver three labels: **OK compost INDUSTRIAL, OK compost HOME, and OK biodegradable MARINE**. For each of these labels, the four essential steps presented before will be required: chemical characterization, biodegradation, disintegration, and ecotoxicity testing.

Any study of compostability of marine environment biodegradation is dependent on the sample tested, its biodegradation, and disintegration kinetics. Therefore, for all test durations indicated in the table below, the maximum duration was considered, but the tests may end earlier in the case of a positive behaviour of the samples. All the analyses required to achieve a complete report, enabling the certification of the product are summed up in Table 3, whereas the required samples and maximum test durations are summed up in Table 4.

Table 3: Sum up of the TUV Austria labels requirements

Name & Standard	***Requirements***
OK compost INDUSTRIAL (EN 13432)	- Heavy metals: non-toxic and non-included in REACH's list - Infra-red analysis, total organic carbon analysis - Biodegradation: 90% in 6 months - Disintegration: 90% in 6 months - Ecotoxicity: non-toxic on 2 plant species

OK compost HOME (NF-T 51800)	- Heavy metals: non-toxic and non-included in REACH's list - Infra-red analysis, total organic carbon analysis - Biodegradation: 90% in 12 months - Disintegration: 90% in 6 months - Ecotoxicity: non-toxic on 2 plant species
OK biodegradable MARINE (ASTM D6691)	- Heavy metals: non-toxic and non-included in REACH's list - Infra-red analysis, total organic carbon analysis - Biodegradation: 90% in 6 months - Disintegration: 90% in 6 months - Ecotoxicity: 90% of survival of daphnia magna

Regarding the standards for the composting conditions, materials and components from natural origin, which were not modified by chemical methods, such as wood, wood fiber, cotton fiber, starch, or paper, should be recognized as biodegradable without being submitted to trials. They should however be chemically characterized (2.4.1) and be compliant with the disintegration and compost quality criteria.

Table 4: Sum up of required sample quantity and form, and durations, by steps

Steps	*conditions*	*Needed sample quantity and form*	*Duration*
Biodegradation	**OK industrial compost**	3x 100g (powder)	Up to 6 months
	OK home compost	3x 100g (powder)	Up to 12 months
	OK marine environment	3x ≈200 mg (depends on the percentage of carbon) (powder)	Up to 6 months
Disintegration	**Lab-scale industrial compost**	700 cm^2 (2-3 A4) (film or sheet)	Up to 6 months
	Lab-scale home compost	700 cm^2 (2-3 A4) (film or sheet)	Up to 6 months
	OK compost	10 kg (final form)	3 to 6 months (same test for industrial & home compost)
	OK marine environment	3x 2 x 2 cm (and at least 3 g) (final form)	3 to 6 months
Ecotoxicity	**OK compost**	See disintegration	Up to 25 days, after disintegration
	OK marine environment	See disintegration	48h, after disintegration

FlexFunction2Sustain offers those biodegradation evaluation services as a result of the BIODEGRADIX lines upgrades, to support the development of biodegradable packaging materials. From screening tests of raw materials and semi-finished structures, to identify the most promising formulations, to complete products biodegradability evaluation, we are now fully equipped to successfully support our clients willing to test the end-of-life behaviour of their products, before placing them on the European market.

3. Conclusions

Deliverable 3.5 presented the services involved in a "Circularity by design" approach, such as product design for recyclability, LCA, compounding, recyclability evaluation, and biodegradability evaluation, available in the Facility Clusters 5 & 6 of the Open Innovation Test Bed project FlexFunction2Sustain. The executive summary and more detailed description of all the services and certification possibilities have been assembled in a report form.

Complementary recapitulative tables were gathered in a public catalogue, including all the spec-sheets of facilities for circularity by design. This catalogue is made available on the FlexFunction2Sustain website (https://flexfunction2sustain.eu), and is attached to the present report in the Appendix. The Catalogue of "Circularity by design" services also includes the links to the other catalogues of services provided by the OITB. Those are: the "Executive summary and full list of collected facility specifications", describing the Lab-2-Fab Facilities for nano-functionalisation of plastic and paper surfaces and membranes (to be presented in D2.6), the "Catalogue of Physicochemical and Functional Characterisation Services" (presented in D4.1) and the "Catalogue of services for safety and regulatory compliance testing" (to be presented in D4.4). In a nutshell, those catalogues present complementary services to produce innovative structures and assess the recyclability and industrial feasibility of the developed sustainable products.

The catalogue of "Circularity by design" services is subject to continuous updating to integrate new elements when they become available. In particular, the accreditation applications to Recyclass and TÜV Austria are pending and final recognition of IPC should occur respectively in April 2022 and December 2022. This report detailed the state of progress on the 30th of June 2022.

4. Degree of progress

Deliverable 3.5 is fulfilled by 100 %. A public catalogue of facilities for “circularity by design”, design for recycling, compounding, recycling, and biodegradability tests has been delivered and will be integrated into the Service Catalogue to be offered by the FlexFunction2Sustain OITB through the Single-Entry Point (SEP). This service catalogue will be a living document, which will evolve together with the technological capabilities of FlexFunction2Sustain's partners and the needs of the project and future customers.

5. Dissemination level

Deliverable D3.5 "Executive summary and spec-sheets of facilities for “circularity by design”, compounding, and recycling and biodegradability tests is a public document, and version 1.0 is available for download.

References

[1] «Recyclability definition,» [En ligne]. Available: https://recyclass.eu/recyclability/definition/.

[2] Recyclass, «Sorting evaluation protocol for plastic packaging,» [En ligne]. Available: https://recyclass.eu/wp-content/uploads/2021/10/SORTING-EVALUATION-PROTOCOL-FOR-PLASTIC-PACKAGING_FINAL-V1.0.pdf.

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Appendix I

The “Executive summary and spec-sheets of facilities for “circularity by design”, compounding and recycling and biodegradability tests” is attached in a catalogue form in this section.

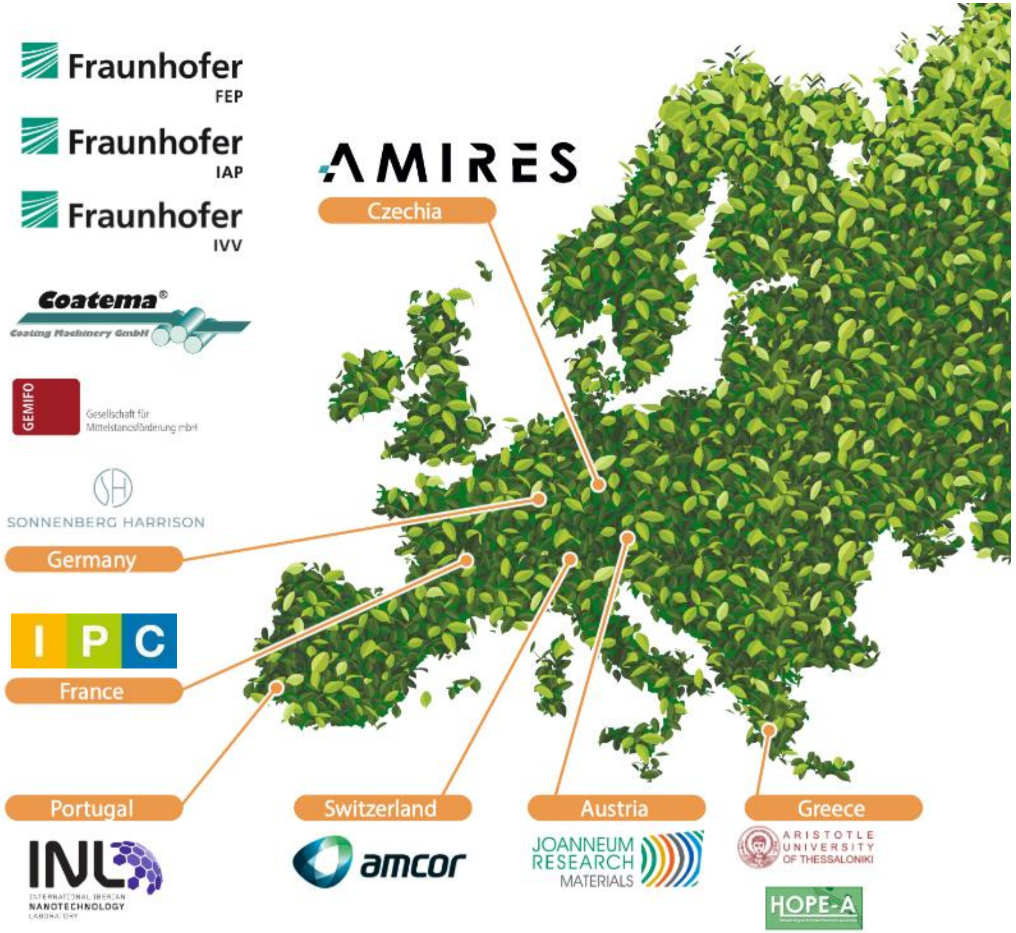
Executive summary and spec-sheets of facilities for circularity by design

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n°862156

The facilities at a glance

- Use Cases of the FlexFunction2Sustain project (p. 3)
- “Circularity by design” concept (p.4)
- Eco-design services (p.5)
- Processing facility for formulation & converting (p.7)
- Recyclability evaluation (p.10)
- Biodegradability evaluation (p.17)
- Interconnection between all the OITB services (p.22)

Service Providers in FlexFunction2Sustain



Use Cases of the FlexFunction2Sustain project

FLEX FUNCTION 2 SUSTAIN

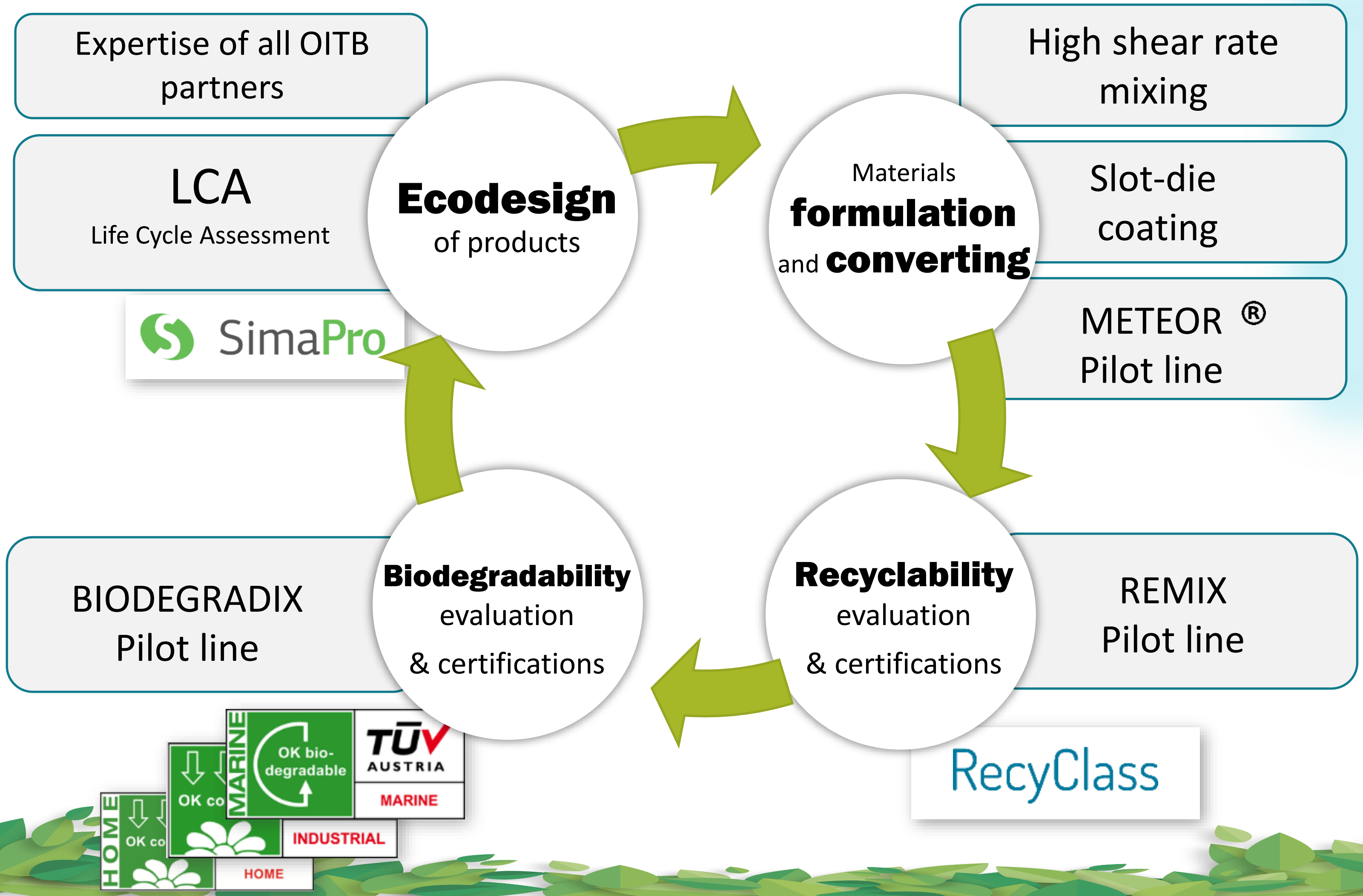
FlexFunction2Sustain's technical facilities and the performances of novel nano-functionalised surfaces will be demonstrated and validated by Europe's leading companies within six industrial application scenarios. Application examples for the services related to the Use Cases are labelled with a code specific for each one (UC#)

Industrial Validation in 6 Use Cases

UC1	UC2	UC3	UC4	UC5	UC6
HUECK FOLIEN	P&G	i3 Your Companion Life Science Filtration	CRF	Capri-Sun	SONAE MC
Biobased Optical Films for Labelling of Consumer Goods and Surface Design	Marine degradable shampoo sachets	Selective and switchable water filter membranes	Multifunctional scratch resistant surfaces in automotive	Recyclable mono-polymer drink pouches	Sustainable paper-based food packaging

A full description of the six Use Cases can be found in the FlexFunction2Sustain Project Handbook, available at https://flexfunction2sustain.eu

"Circularity by design" concept & link with other FF2S services



+ Functionalisation
(Lab-2-Fab facilities within the OITB)

Executive summary and spec-sheets of facilities for circularity by design

Eco-design supported by expertise

Expertise		
Functionalities	Technical specifications	Application examples
Design for Recycling flexible plastic and paper surfaces and membranes	- Expertise in food and pharma packaging, membrane-based filter systems, printed electronics, and more - Supporting customers at early development stages to minimize the risk of innovation in Eco-design - Design according to legislation and internationally recognized recycling protocols	Capri-Sun Use Case (UC5): Design of novel recyclable packaging materials for drink pouches P&G Use Case (UC2): Design of marine degradable shampoo sachets

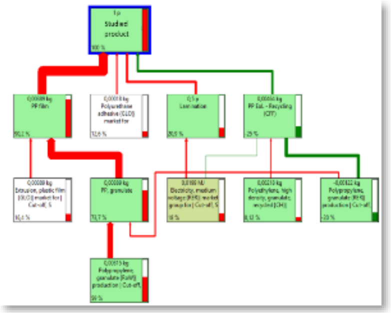
Application examples:
Top: Capri-Sun drink pouch
Bottom: P&G Marine degradable shampoo sachets

Executive summary and spec-sheets of facilities for circularity by design

Eco-design supported by Life Cycle Assessment

Life Cycle Assessment			
Functionalities	Tools	Technical specifications	Application examples
Identification of environmental impacts	Life Cycle Inventory Sheets SimaPro Software Ecoinvent 3.0 database Product Environmental Footprint (PEF) GulPlug energy consumption measurement equipment	Cradle-to-gate studies Cradle-to-grave studies Cradle-to-cradle studies Screening LCA Continuous energy consumption measurements of up to 6 machines simultaneously	Comparative LCA between non-recyclable, recyclable, and biodegradable structures (UC1) Comparative LCA to identify the best End of Life scenario for an innovative product (UC3) Comparative LCA between commercial reference and 3 monomaterial structures to identify which replacement solution is the more environmentally friendly (UC5)

Lifecycle overview* from SimaPro Software



* Image available in a better resolution in the Executive Summary associated to this catalogue (link to be updated upon publication)

Executive summary and spec-sheets of facilities for circularity by design

Materials formulation and converting

Formulation

Converting

Lab-2-Fab facilities examples

High shear rate mixing

METEOR ® Pilot line

R2R UV imprinting Pilot line

Co-extrusion Pilot line

Details in next slides

Slot-die coating

Details in another catalogue*

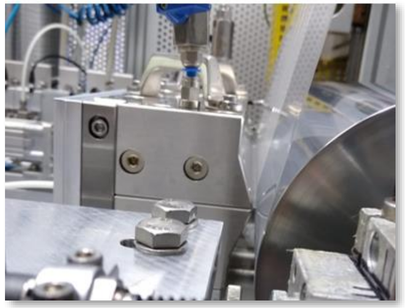
*Link to be updated upon publication of the corresponding catalogue

Executive summary and spec-sheets of facilities for circularity by design

Processing facility for formulation & converting

Upgraded lines for coating preparation & processing			
Functionalities	Equipment	Technical specifications	Application examples
High shear rate mixing	Planetary ball mill	Homogeneous dispersion formulations through high shear rate mixing for the development of high-barrier coating materials	Gas barrier layer development for the mono-material based laminate production for drink pouches (UC5) More details in the public deliverable D3.1
Slot die coating process	Roll-to-roll Coating and Lamination line	Pumping with a syringe pump or extender-screw pump. Pre-heating and degassing possibility in a pressure tank Coating Width: 300 mm	Gas barrier coating application for the mono-material based laminate production for drink pouches (UC5) More details in the public deliverable D3.1

Upgraded lines @IVV:
Top: High Shear Rate Mixing
Bottom: Slot die coating



Executive summary and spec-sheets of facilities for circularity by design

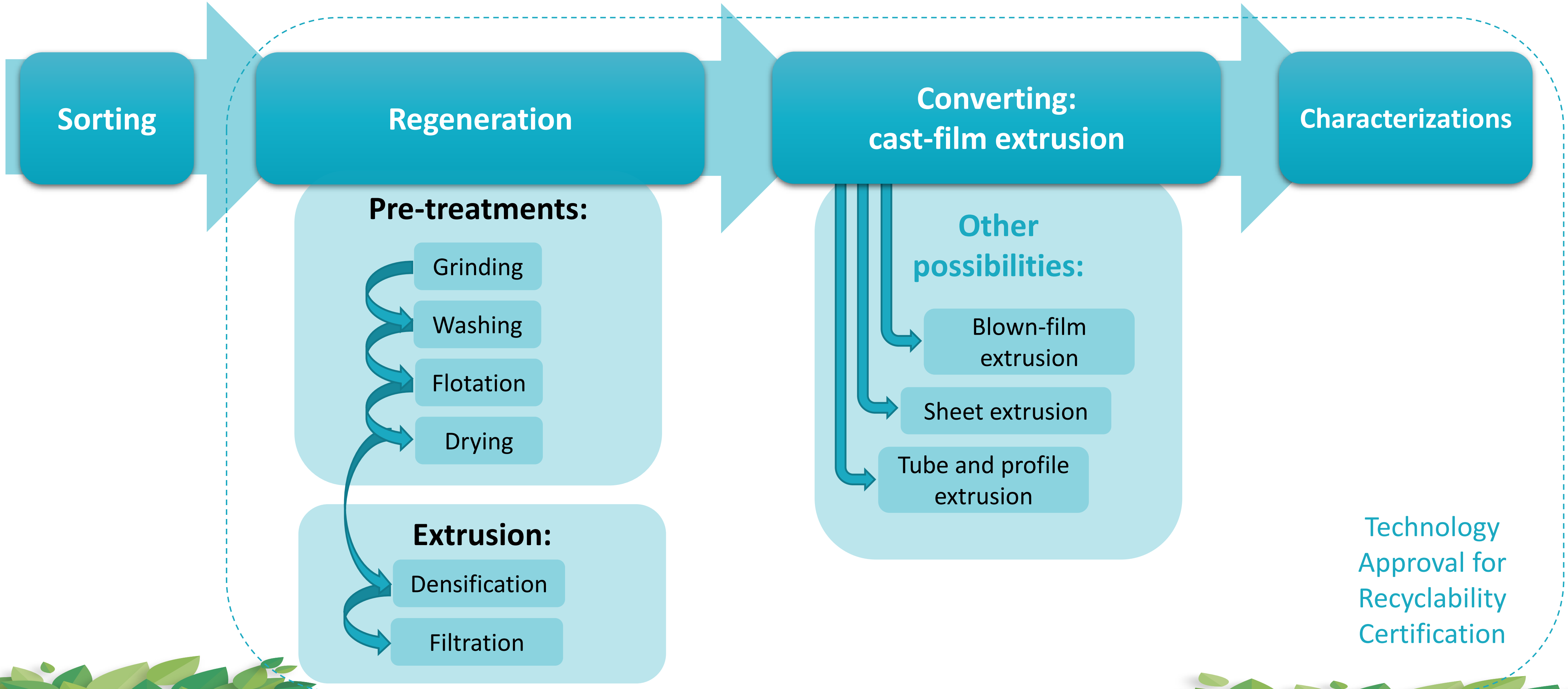
Processing facility for formulation & converting

Upgraded METEOR pilot line			
Functionalities	Equipment	Technical specifications	Application examples
Compounding & converting in one step	METEOR® pilot line (patented) On-line rheometer Flat die Scamex cast line with take-off station	Compounding and specific material formulations development with an efficient dispersion of additives while reducing the thermo-mechanical degradation of the material - Film coextrusion - High temperatures, up to 300°C, - Compounding process throughput range: from just a few kg/h up to 100 kg/h - Line speed: 0 to 35 m/min - Films thickness range: 25 to 250 µm - Films width: 300 to 330 mm	Compounding PLA with crosslinking additives in order to improve its thermal stability (UC1)

METEOR equipped with the cast line @IPC

Executive summary and spec-sheets of facilities for circularity by design

Recyclability evaluation – REMIX pilot line



Executive summary and spec-sheets of facilities for circularity by design

Recyclability evaluation – REMIX pilot line

Upgraded sorting evaluation			
Functionalities	Equipment	Technical specifications	Application examples
Optical sorting	Mistral+ Connect DVI 1200 - Pellenc ST equipped with a high-resolution sorting bar	Near Infra-Red and visible spectra detection Assessment of sortability with static and dynamic tests - Samples: films or rigid materials, 20mm to 350mm, max 10kg/m² - Maximal flow rate: 1 to 3t/h, depending on samples area density	Verification of compatibility with existing sorting technologies for recyclable innovative packaging (UC5)

Mistral+ Connect DVI 1200 sorting machine (Pellenc ST) @ IPC

Executive summary and spec-sheets of facilities for circularity by design

Recyclability evaluation – REMIX pilot line

Pre-treatments			
Functionalities	Equipment	Technical specifications	Application examples
Grinding	Shredder Alterval MR17-40	Size reduction, especially for films - 3 grid sizes: 10, 20 and 30 mm - Maximum flow rate: 150 kg/h	Recyclability evaluation with existing technologies for innovative packaging (UC5)
Washing	Sorema washing pilot line	- Tank capacity: 20 L - Vibrating sieve & cyclone drying	
Sink-float separation	Auger dynamic flotation pilot line	Sinking and floating fractions recovery - Vibrating feeding - Tank capacity: 4.4 m^3 - 5 successive mixing rollers	

Pre-treatment equipment:
Top: shredder
Middle: washing pilot line
Bottom: flotation pilot line

Executive summary and spec-sheets of facilities for circularity by design

Recyclability evaluation – REMIX pilot line

Extrusion & Converting			
Functionalities	Equipment	Technical specifications	Application examples
Thermodensification	Wanner thermogranulator	Transforms ground films into pellets to enable their processing through further standard techniques - Max temperature: 400 °C - Max flow rate: 20 kg/h	Recyclability evaluation with existing technologies for innovative packaging (UC5)
Extrusion - Filtration	Clextral extruder EVOLUM 32 HT Filtering system Maag HSC-050	- Max temperature: 400 °C - Max screw rotation speed: 800 rpm - Max flow rate: 100kg/h - Filtration area Ø 50 mm - Filters fineness: 105 µm, 150 µm, 300 µm, 500 µm (other sizes on demand)	
Converting: cast-film extrusion	Flat die Scamex cast line with take-off station	- Max temperature: 300 °C - Line speed: 0 to 35 m/min - Films thickness range: 25 to 250 µm - Films width: 300 to 330 mm	

Extrusion equipment:
Top: Thermogranulator
Bottom: Filtering system

Executive summary and spec-sheets of facilities for circularity by design

Recyclability evaluation – REMIX pilot line

Characterisations of recycled pellets			
Analysis	Equipment	Technical specifications	Application examples
Bulk Density	- Apparatus for the determination of bulk density - 2000 ml.	According to ISO 15344	Evaluation of the recyclates quality to support their recyclability evaluation with existing technologies for innovative packaging (UC5)
Density	- Precision scale METTLER TOLEDO AE240 ; - Accessories for density measurement.	According to ISO 1183-1	
Melt Index	- Melt Flow Indexer GOTTFERT Mi-40 ; - Capillary die, length 8 mm and diameter ≈ 2.1 mm ; - Precision scale METTLER TOLEDO AE200 ; - Ventilated oven HERAEUS UT 6060.	According to ISO 1133	
Ash content	- Muffle furnace NABERTHERM ; - Precision scale METTLER TOLEDO AE200	According to ISO 3451-1	
Differential Scanning Calorimetry	- DSC calorimeter Q100 TA Instruments ; - Indium reference standard ; - Plomb reference standard ; - Precision scale METTLER TOLEDO AE240.	According to ISO 11357-3	

Differential scanning calorimetry (DSC) @IPC

Executive summary and spec-sheets of facilities for circularity by design

Recyclability evaluation – REMIX pilot line

Characterisations of recycled pellets & films

Analysis	Equipment	Technical specifications	Application examples
Volatiles	- Ventilated oven HERAEUS UT 6060 ; - Precision scale METTLER TOLEDO AE200 ; - Timer NOVO 82110.		Evaluation of the recyclates quality to support their recyclability evaluation with existing technologies for innovative packaging (UC5)
Colorimetry	- Spectro guide BYK Gardner.	L*,a*,b* measures	
Thickness	- Heidenhain thickness gauge.	According to ISO 4593	
Tear Strength	- Zwick/Roell BT2-FR005TH.A50	According to EN ISO 6383-1	
Tensile properties	- Dynamometer ZWICK 1.0 ; - 1 kN sensor ; - Thermo-hygrometer TESTO TERM 6010 ; - Digital micrometer 25 mm;	According to ISO 527-3	
Dart Impact	- Dart Tester	According to ISO 7765-1	
Gels and Specks	- Microscope VHX-7100 KEYENCE.		

Dart Tester @IPC

Executive summary and spec-sheets of facilities for circularity by design

Recyclability evaluation – REMIX pilot line

Certification possibilities (Recyclass)	
Name	Technical specifications
Technology Approval	- Packaging not entirely covered by Recyclass' Design for Recycling guidelines - The packaging will follow the Recyclability Evaluation Protocol for PP Films (also available for PE) - Input: 10 kg of innovative packaging & 25 kg of control film
Design for Recycling Certification	- Packaging entirely covered by Recyclass' Design for Recycling guidelines - The technical recyclability of the packaging will be audited for the EU market, based on the existence of a recycling stream and the packaging's structure.
Recyclability Rate Certification	- Packaging entirely covered by Recyclass' Design for Recycling guidelines - The effective recyclability of the packaging will be audited for the specific geographical area of the certification body, based on the existence of a recycling stream and the packaging's structure.
Letter of Compatibility	- Semi-finished packaging - The semi-finished packaging will be audited, based on the existence of a recycling stream and the packaging's structure.

Example of Recyclass logo for a recyclable packaging

Executive summary and spec-sheets of facilities for circularity by design

Biodegradability evaluation – BIODEGRADIX pilot line

- Quality of the material
- Biodegradation
- Disintegration
- Ecotoxicity

Industrial composting | **Home composting** | **Marine environment**

Certification possibilities

Executive summary and spec-sheets of facilities for circularity by design

Biodegradability evaluation – BIODEGRADIX pilot line

Biodegradation monitoring			
Functionalities	Equipment	Technical specifications	Application examples
Biodegradability evaluation in **industrial compost** conditions	36 channels ECHO Respirometer	Samples: 3x 100 g (powder) Temperature: 58 °C Duration: up to 6 months	Biodegradation of samples: screening for the selection of a formulation (UC1)
Biodegradability evaluation in **home compost** conditions	12 channels ECHO Respirometer	Samples: 3x 100 g (powder) Temperature: 25 °C Duration: up to 12 months	Biodegradation evaluation of the raw material (UC6)
Biodegradability evaluation in **marine environment**	12 channels ECHO Respirometer	Samples: 3x ≈200 mg (depends on the carbon content) (powder) Temperature: 30 °C Duration: up to 6 months	Biodegradation of samples (UC2)

12-channel respirometers
Left: for home compost
Right: for marine conditions

Executive summary and spec-sheets of facilities for circularity by design

Biodegradability evaluation – BIODEGRADIX pilot line

Disintegration evaluation			
Functionalities	Equipment	Technical specifications	Application examples
Lab-scale disintegration evaluation in **industrial compost** conditions	Heat chamber Reversal film frames Incubators	Samples: 700 cm² (2-3 A4 sheets)(film) Temperature: 58 °C for 90 days, then 25 °C Duration: up to 6 months	Disintegration of samples: study of the impact of crosslinking on PLA disintegration (UC1)
Lab-scale disintegration evaluation in **home compost** conditions	Heat chamber Reversal film frames Incubators	Samples: 700 cm² (2-3 A4 sheets)(film) Temperature: between 20 °C and 30 °C Duration: up to 6 months	Disintegration of samples: identification of the impact of a coating on a paper (UC6)
Pilot-scale disintegration evaluation in **composting** conditions (valid for both industrial and home compost)	6 thermally insulated tanks	Samples: 10 kg (final form) Self-heating Duration: 3 to 6 months	Disintegration of samples: evaluation of their behaviour upon self-heating composting process
Disintegration evaluation in **marine environment**	Heat chamber	Samples 3x 2x2 cm (and at least 3 g) Temperature: 30 °C Duration: up to 84 days	Disintegration of samples: screening for the selection of a formulation (UC2)

Thermally insulated tanks for pilot-scale disintegration in composting conditions

Executive summary and spec-sheets of facilities for circularity by design

Biodegradability evaluation – BIODEGRADIX pilot line

Ecotoxicity evaluation			
Functionalities	Equipment	Technical specifications	Application examples
Ecotoxicity evaluation in **compost** conditions (valid for both industrial and home compost)	Heat chamber Lights	Samples from pilot-scale disintegration (see previous slide) Duration: 21 days after 50% of seedling emergence	Ecotoxicity evaluation of samples' degradation products
Ecotoxicity evaluation in **fresh water environment** (as used in marine environment certification)	*Daphnia Magna* (planktonic crustacean)	Samples 3x 2x2 cm (and at least 3 g) Duration: 3 to 6 months incubation + 48 h	Ecotoxicity evaluation of samples's degradation products in the aquatic environment, screening for the selection of a formulation (UC2)

Organisms studied for the ecotoxicity tests:
Top: wheat plants,
Bottom: *Daphnia Magna*

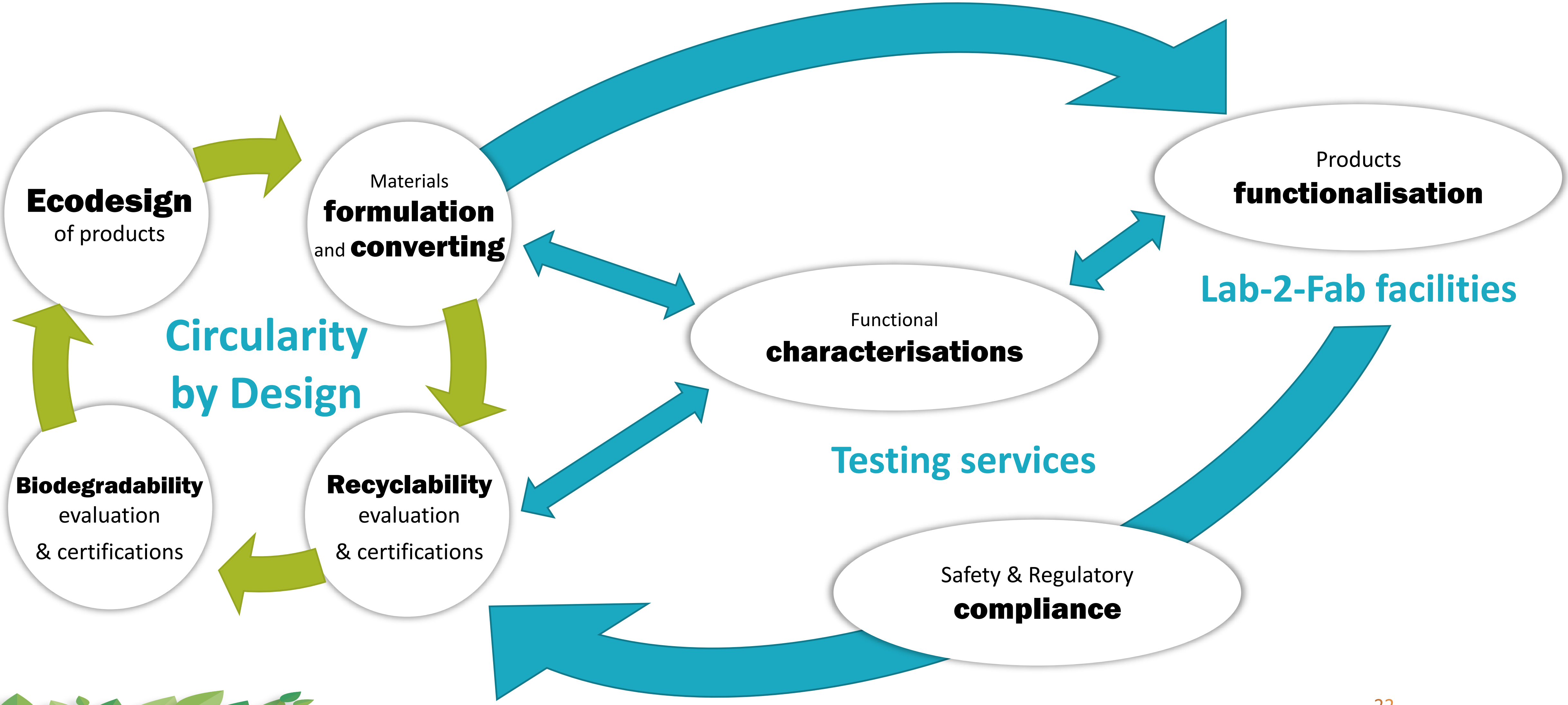
Executive summary and spec-sheets of facilities for circularity by design

Biodegradability evaluation – BIODEGRADIX pilot line

Certification possibilities	
Name & Standard	Requirements
OK compost INDUSTRIAL (EN 13432)	- Heavy metals: nontoxic and non-included in REACH's list - Infra-red analysis, total organic carbon analysis - Biodegradation: 90% in 6 months - Disintegration: 90% in 6 months - Ecotoxicity: non-toxic on 2 plant species
OK compost HOME (NF-T 51800)	- Heavy metals: nontoxic and non-included in REACH's list - Infra-red analysis, total organic carbon analysis - Biodegradation: 90% in 12 months - Disintegration: 90% in 6 months - Ecotoxicity: non-toxic on 2 plant species
OK biodegradable MARINE (ASTM D6691)	- Heavy metals: nontoxic and non-included in REACH's list - Infra-red analysis, total organic carbon analysis - Biodegradation: 90% in 6 months - Disintegration: 90% in 6 months - Ecotoxicity: 90% of survival of *Daphnia magna*

Logos of TÜV Austria for the aimed certifications

Interconnection between all the OITB services



Interconnection between all the OITB services

Link with the other FlexFunction2Sustain services		
Lines	Technical specifications	References to other catalogues
Lab-2-Fab facilities for nanofunctionalisation plastic and paper surfaces and membranes	- Vacuum coating processes for nano-surface modification - Atmospheric pressure processes for film extrusion, coatings and lamination - Nano-structuring of surfaces - Smart functionality: printed electronics	See Executive summary and full list of collected facility specifications*
Functional characterisations	- Gas barrier testing - Testing of electrochemical properties - Assessment of mechanical properties, integrity, and durability - Optical properties characterisation - Surface and microstructure analysis - Thermal and rheological properties - Test specimen preparation	See Catalogue of physiochemical and functional characterisation services
Food compliance test facilities and health safety testing facilities	- Migration testing and safety assessment - Microbiological safety assessment - Off-Flavours testing - Analysis of Volatile Organic Compounds (VOCs) - Nano-material safety and risk assessment - Advice on Regulatory Compliance	See Catalogue for services for safety and regulatory compliance testing*

*Links to be updated upon publication of the corresponding catalogues

An example customer project

- Do you want a recyclable food packaging? Here‘s how to:

- Definition of product specifications (SEP, INL, FHG-IVV, customer)
- Film Extrusion (FHG-IVV or IPC)
- Gas Barrier Coating Tests (FHG-FEP | FHG-IVV | AMCOR)
- Lamination (FHG-IVV | AMCOR)
- Food contact verification (INL)
- Recyclability test (IPC)
- Piloting |Yield and quality verification | cost assessment (AMCOR & Co.)

FLEX FUNCTION 2 SUSTAIN