In-built Triggered Enzymes to Recycle Multi-layers: an Innovation for Uses in plastic-packaging

D8.7: Initial technology integration action plan

WP8: Communication, dissemination and exploitation activities; assessment of legislative and economic aspects

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1 Table des matières

Abbreviations

ML: MultiLayer

FCM: Food Contact Materials

PUD: Polyurethane dispersion

NIR: Near InfraRed

Executive summary

TERMINUS project addresses the challenge of recycling multi-layer and multi-compound packaging by developing biodegradable, smart enzyme-containing polymers acting as tie-layers and/or adhesives in these applications.

Deliverable D8.7 is the initial version of the technology integration plan that proposes a strategy to integrate the project outputs within the current structures of the packaging and recycling industries. This action plan will take into account the needs and constraints of industries and recycling centers as well as those of the packaging producers.

The deliverable includes a methodology especially designed by the consortium to address this road mapping. The methodology was supported by the following steps:

- **Overview of key steps** of the current production and end-of-life management process.
- **Identification of the needs and constraints** of multilayers packaging manufacturers, sorting and recycling centers.
- **Identification of all the elements inside this value chain that will be impacted** by the TERMINUS technology.
- **Identification of external elements** that will impact the TERMINUS technology.
- A deeper description of the **key integration points** and how the project will be impacted by those elements and how it shall adapt.

Ultimately, based on this detailed description of key integration points, a set of milestones will be proposed to pave the way for future integration action plan.

1 Introduction

To develop the technology integration action plan that will integrate the project outputs within the current structure of the packaging and recycling industries' value chain, a methodology was developed by the partners. This methodology will be used to identify the key integration points needed to be addressed by any third parties willing to include the project technology within their businesses.

Finally, from these key integration points, several milestones were proposed to create the different steps of the action plan.

2 Methodology

To propose a suitable technology integration roadmap, a specific methodology was developed (see Figure 1) and supported by the following steps:

- Description of all elements of the packaging production and end-of-life value chain with an **overview of the key steps** and the **needs and constraints** from an industrial and recycling center perspective
- Identification of all the **elements of the value chain impacted** by the TERMINUS technology or **external elements that will impact the technology**.
- A description of the **key integration points** including adaptation of the existing industrial processes

Ultimately, based on this detailed description, a set of milestones will be proposed to develop an integration action plan.

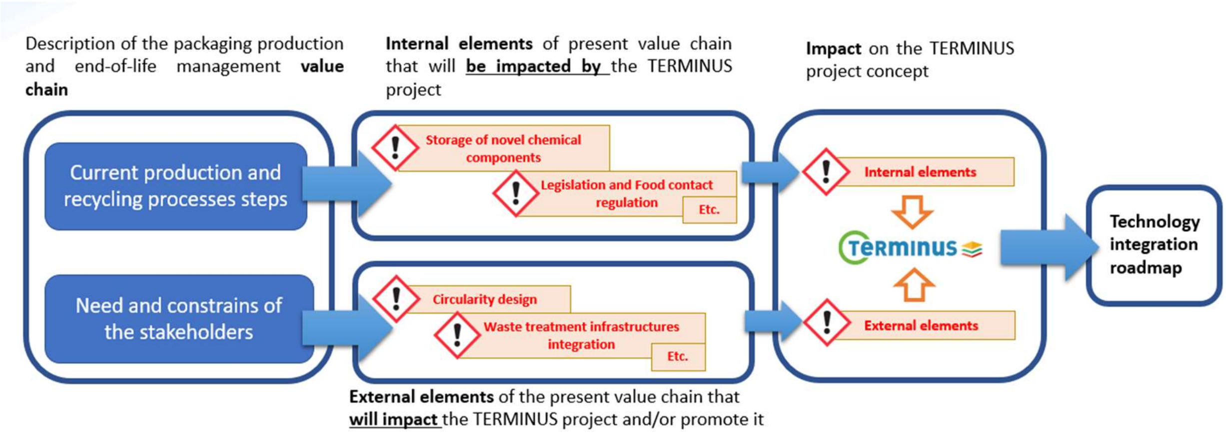

Figure 1:Technology integration methodology for the TERMINUS project results valorisation

3 State of the art of current production and recycling processes

3.1 Schematic overview of the main steps

The objective of the deliverable is the development of an action plan defining the integration of TERMINUS technology in packaging production and in the recycling process. An initial flow chart of the current production and recycling process is proposed in Figure 2. The scheme highlights the elements of the value chain that **will be strongly impacted and adjusted based on TERMINUS results**. Hence, it will allow in a later stage to ensure a smooth integration of the new process steps into the current production and recycling facilities.

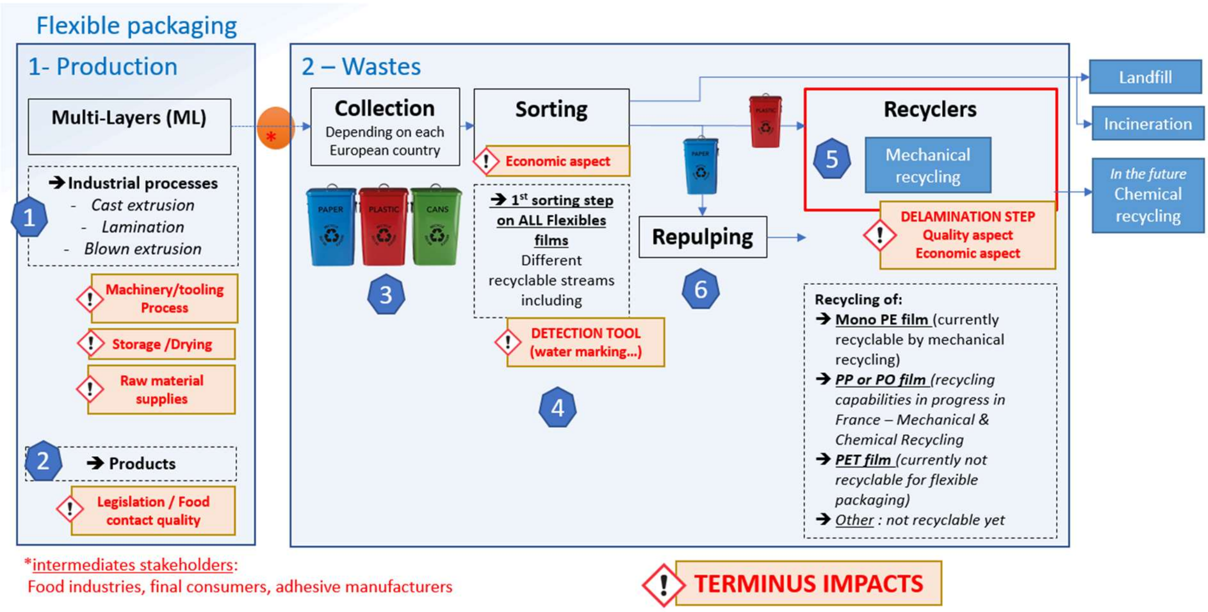

Figure 2: Overview of current production and recycling processes of ML

3.1.1 Industrial processes for the production of multi-layer packaging

Multilayer materials for packaging are produced in several ways. This project addresses the following four processes.

3.1.1.1 Lamination processes for polyurethane based adhesive

3.1.1.1.1 Description of the technologies

Flexible packaging adhesives are predominately based on urethane chemistry, acrylic chemistry starting to be reported regularly. Urethane backbone options create unique performance properties. Changes in composition determine whether the adhesive will be solvent-less, solvent or water based. While the starting components are limited to European compliance lists, the resultant adhesives are complex. These meet the challenges from simple, non-demanding packages to the most severe requirements. The urethane-based adhesives are commercially available as single component or as two-components (to be mixed right before being used) products. In both cases, they are available as solvent based solution, solvent-less and waterborne (called Polyurethane Dispersion - PUD).

- **Solvent- and water based adhesive lamination**: Solvent- and water based adhesives contain solvent or water as a carrier, which is subsequently dried after application (dry bond laminating), leaving the active resin system on the substrate to be bonded to a secondary substrate to make the lamination. The main advantage of this process is the use of solvent with low viscosity that allows a good dispersion of the polyurethane. Viscosity values at 25°C are from 15 to 1000 mPas. The disadvantage comes from the need of drying to remove the solvent from the substrate. The adhesive is exposed to a warm airflow. Standard values are 1 m³/s at 80°C. The next lists show main advantages and disadvantages of water and solvent base approaches:

Technology	Advantages	Disadvantages
PUD lamination (waterborne adhesives)	• medium to high solids at lower viscosity • little to no VOC • performance equal to general purpose and medium performance solvent base and 100 % solid content adhesive • good bonds to wide range of substrates • good to excellent clarity • can be cost competitive • reduced health and safety issues	• tendency to generate foam that induced gap in bonding • usually not freeze/thaw stable • requires careful addition and mixing of co-reactant to ensure proper dispersion
Solvent-based lamination	• well known history of performance • types available for all types of food packaging laminations • can be available as a single component for simplicity of handling • two components adhesives enhance heat, chemical and, in some cases, bond performance • excellent clarity • adhesion to wide range of substrates • newer chemistries allow higher solids application •	• contain volatile organic compounds (VOC), though many Hazardous Air Pollutant (HAP) free • can be economical too costly on dried applied basis • health and safety concerns • fire hazard • curing can be compromised by water contamination • rate of drying often limiting step • takes time for cure to develop

- **Solvent free adhesive lamination**: Solvent free adhesives are 100% active products containing no water or solvent carrier. They are applied to base substrates using smooth roll transfer, solvent free laminators and subsequently nipped/bonded to the secondary film to make the lamination. Advantage and disadvantage are reversed. The two components are heated up to 50°C to adjust viscosity (it is the only way to do it). Viscosity values at 25°C are from 1.500 to 20.000 mPas.

Technology	Advantages	Disadvantages
Solvent free adhesive lamination	• little or no VOC and no HAP • high application speeds • very competitive on applied cost • often lower applied weight	• need dedicated laminator to apply • need transfer pumps for mono-component products • little initial bond, no shear resistance initially

	• adhesion to wide range of substrates • types available for low to high demanding packaging • excellent clarity • reduced waste of adhesive •	• some need pre-heat to pump and apply • takes time for bond and final cure to develop • two-components products require proper mixing and ratio, especially in higher performance applications, and specific equipment (meter-mix-dispenses pump)

The general scheme of a laminating machine is presented in Figure 3. In the case of solvent-bases adhesives application, only an oven is integrated along the passage of the film.

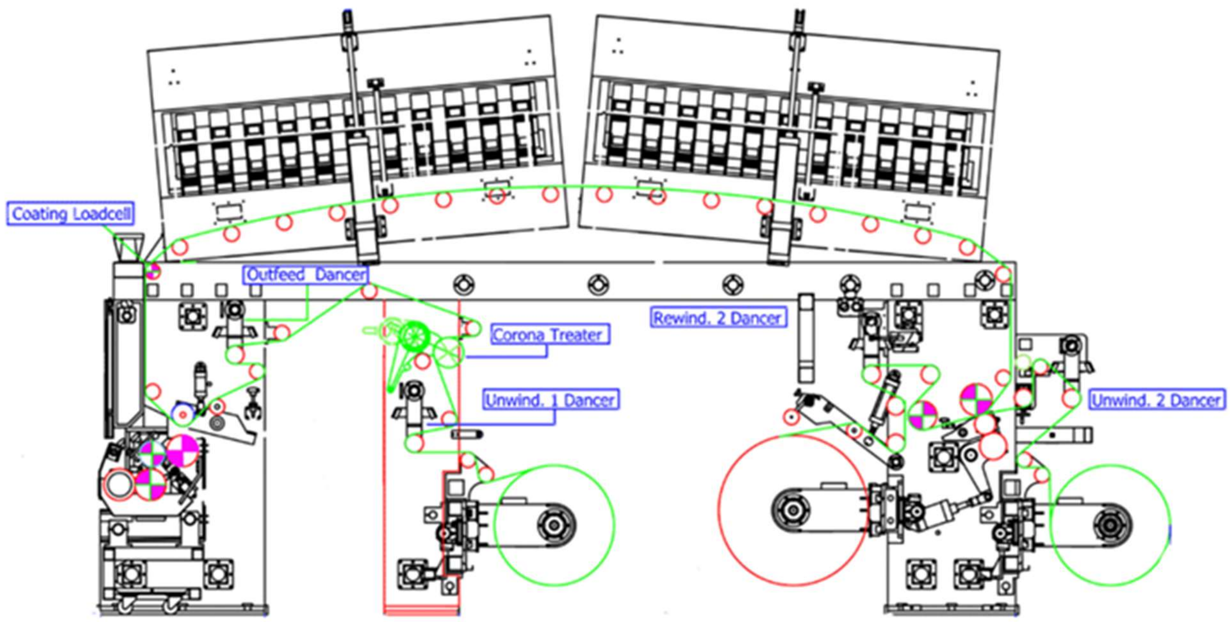

Figure 3:General scheme of the laminating PUR adhesives process for the elaboration of multilayer food packaging films.

3.1.1.1.2 Envisaged TERMINUS impacts in specific stages of the process

Raw material supplies
The incorporation of enzymes (enzyme-protected system) to PUR formulations in any of the modalities will involve, in a first approach, an efficient setting of acquisition and logistics mechanisms to provide the functional material from the adhesives stakeholders (in charge of enzyme-containing PUR formulations) to the laminating entity.

Storage stage of raw material and finished products
Regarding the raw materials, the new enzyme-containing PUR formulations would possibly require adjustments or redesign of storage conditions given the demands on enzymes preservation in time, humidity and temperature to be previously defined by the adhesives stakeholder. On the other hand, the storage conditions of finished multilayer films would possibly be dictated by the modifications on curing kinetics and physical characteristics of films (i.e. adhesive's thickness and surface density) derived from the presence of the enzymes regarding activity, dimensions and quality of dispersion.

Machinery/tooling
The need for ensuring the homogeneous dispersion and distribution of the enzymatic material into the PUR formulation would create possibly the need for specific mixing steps and devices either by modification of the existing ones or the integration of new systems. Furthermore, the material weight control of the coated layer might be also impacted. These modifications would be linked to Figure 3 at the zone of the coating load cell.

Processing conditions
The current processing conditions in PUR laminating machines are standardized to a great extent. For example, normal speed in industrial processes may be as high as 350 m/min. With the introduction of the enzyme system, preservation of enzymes' activity against thermal and shear stress effects must be seized as to possibly consider significant adjustments to current process conditions. It is thus also possible that tooling adjustments might be involved.

Quality control of raw material and finished products
The new PUR TERMINUS formulations will involve solid dispersion phenomena and possibly viscosity issues as well as modification of current curing kinetics. It is strongly probable that characterization techniques in the quality control step should be adapted to these new features.

Implementation economics
The different process aspects considered so far as to be impacted by the TERMINUS implementation must be addressed by suitable and efficient exploitation models i.e. technology transfer, patents, etc. and/or business models.

3.1.1.2 Extrusion coating lamination process

3.1.1.2.1 Description of the technology

This process is particularly suited to paper- and board-based structures. The bonding of the extrudate to the webs depends on the polymer temperature. The temperature of the polymer affects the degree of oxidation. The hotter the polymer when it enters the nip, the better it will flow and adhere to the webs. Relatively high temperatures (e.g. 300°C for LDPE) are needed to achieve these effects. Extrusion coating lamination needs a careful balancing of the process conditions especially for the temperature of the molten polymer which affect the degree of oxidation (high temperature is needed).

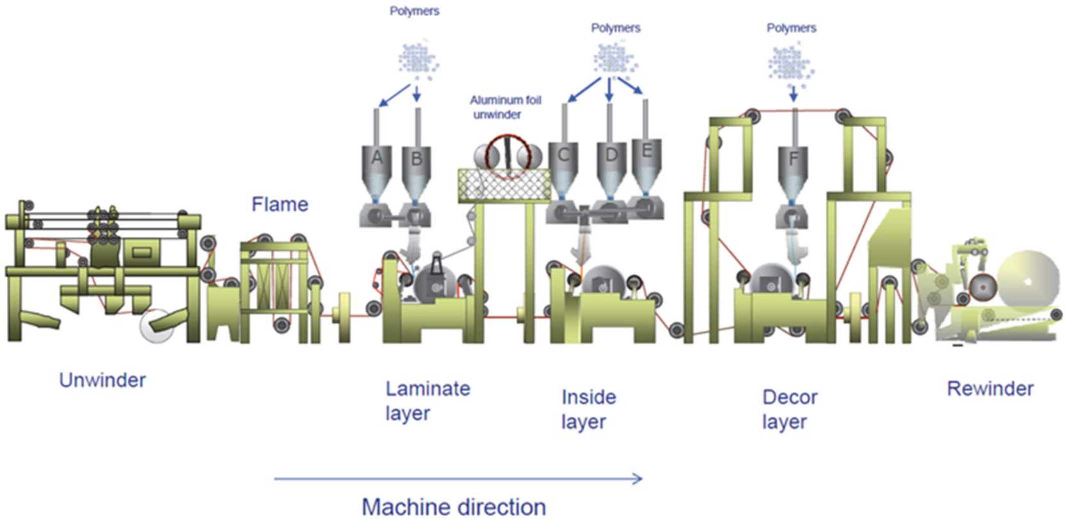

Figure 4: Extrusion coating lamination process

3.1.1.2.2 Envisaged TERMINUS impacts in specific stages of the process

Raw material supplies

In the context of raw material needs for the extrusion coating laminating process, the most favourable approach considers the supply of previously enzyme-containing multilayer films from two processing sources and, thus, stakeholders: PUR laminating and blown extrusion multilayer laminating films. The objective of this was to lowering the normally high temperatures used in the extrusion coating, allowing to preserve the enzymatic activity. Hence, in principle, those stakeholders linked to PUR and blow laminating, would be in charge of the respective supplies through an efficient and adapted logistics.

Storage stage of raw material and finished products

Regarding the raw materials, the received enzyme-containing PUR-based and blown multilayers films would possibly require adjustments or redesign of storage conditions given the demands on enzymes preservation in time, humidity and temperature to be previously defined by the respective stakeholders.

Machinery/tooling

According to the proposed approach, previously fabricated multilayers systems would be used as primary film reels to be released in the main unwinder in Figure 4. New physical characteristics of raw materials as density and dimensions have to be taken into account to evaluate potential modifications in tooling and/or integration of auxiliary equipment.

Processing conditions

Adaptation of processing conditions to demands from biodegradable TL and enzymes' preservation

Quality control of raw material and finished products

The TERMINUS approach will involve solid dispersion phenomena and novel board-based structures. It is strongly probable that characterization techniques in the quality control step should be adapted to these new features on introducing adjustments to optical, adhesion and mechanical tests.

Implementation economics

The different process aspects considered so far as to be impacted by the TERMINUS implementation must be addressed by a suitable and efficient exploitation models i.e. technology transfer, patents, etc. and/or business models.

3.1.1.3 Film blowing co-extrusion process

3.1.1.3.1 Description of the technology

In the blown film co-extrusion technique, two or more resins are extruded through an annular slit die, usually vertically, with the melts being brought together just before the die lips (see 5). The melt coming out of the die is pulled upwards several meters high and fed through a nip formed by two rollers. The nip closes the system off so that air pressure can be applied on the inside to blow the material up in a giant bubble. At the same time, the bubble is air-cooled on the outside and, in some cases, from within. The film thickness is controlled by the output rate and the line take off speed. The blow-up ratio (BUR), i.e. the ratio of the bubble diameter to the die diameter will have an impact on the film physical properties because a higher BUR gives higher TD orientation and vice versa. The bubble collapses at the nip rolls and results in flat tube referred to as lay-flat tube of film. The lay-flat is then slit at the edges to produce two flat film sheets and wound up onto reels.

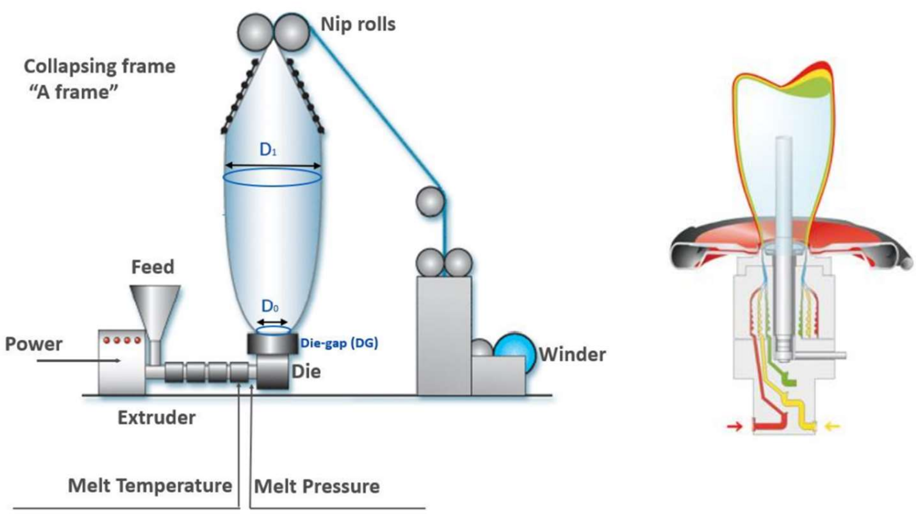

Figure 5: Film blowing co-extrusion process

3.1.1.3.2 Envisaged TERMINUS impacts in specific stages of the process

Raw material supplies

In the context of raw material needs for the film-blowing co-extrusion laminating, the stakeholders in this domain will acquire rough enzymatic material from a stakeholder devoted to this expertise in charge of the supplies. An efficient and adapted logistics would be thus necessary.

Storage stage of raw material and finished products

In the first place, the enzymatic material would require adapted conditions of storage in order to preserve the enzymatic activity and overall material's characteristics. In parallel, attention has to be paid to the tie layers (TL) to be compounded with the enzymes since the biodegradable nature of these also new materials might make them prone to storage conditions adjustments.

Drying needs

The use of biodegradable bioplastics as TL points to particular needs in terms of drying efficiency. This aspect has to be possibly targeted as part of the TERMINUS processing implementation.

Machinery/tooling

The TERMINUS approach involves the compounding step linked to the integration and dispersion of the enzymatic material into the TL. Compounding equipment would be thus necessary to perform the task. At the same time, the need to preserve enzymatic activity and preventing thermomechanical degradation of TL would also make to consider tooling modification like extruders' screw configuration or peripherals devices.

Processing conditions

Adaptation of processing conditions to demands from biodegradable TL and enzymes' preservation.

Quality control of raw material and finished products

The TERMINUS approach will involve solid dispersion phenomena and novel board-based structures. It is strongly probable that characterization techniques in the quality control step should be adapted to these new features on introducing adjustments to optical, adhesion and mechanical tests.

Implementation economics

The different process aspects considered so far as to be impacted by the TERMINUS implementation must be addressed by a suitable and efficient exploitation models i.e. technology transfer, patents, etc. and/or business models.

3.1.2 Products.

3.1.2.1 Food safety Regulation

Characteristics and usage of current multilayer films for food packaging in the context of food contact and environmental regulations are somehow typified (Tables 1 and 2). On the other hand, the use of enzymes in such materials in order to impart specific functions is still far from being defined within the regulatory frameworks. In the case of TERMINUS, the use of enzymes cannot even be considered as a development of smart materials, which standard is available, since the particular functionality of TERMINUS linked to the enzymes will take place after the application life span of the product, it means, during the waste valorisation step. In such a situation, migration test results are key since particular good practice procedures need to be established for TERMINUS.

In addition, the production step shall meet the requirements of several Regulations especially on food contact. For most packaging material producers, **compliance with the food safety Regulation** is of utmost importance. The most important legislations to comply with are the ones defined by the European Union (EU), the USA (FDA) and the Food Safety Law of China. **To ensure this compliance, materials will have to be approved in migration tests**. Indeed, these principles are set out in Regulation (EC) No 1935/2004 and require that materials do not:

a) endanger human health;

(b) bring about an unacceptable change in the composition of the food;

(c) bring about a deterioration in the organoleptic characteristics thereof.

Concerning **the use of plastics for FCM**, the applicable Regulation is (EU) N° 10/2011 on plastic materials and articles intended to come into contact with food. It sets out rules on the composition of plastic FCMs and establishes a Union List of substances that are permitted for use in the manufacture of plastic FCMs. The Regulation also specifies restrictions on the use of these substances and sets out rules to determine the compliance of plastic materials and articles in food contact.

Packaging are required to fulfil the regulations of EU, but also out of Europe Regulations such as USA and China ones. The list of main requirements to fulfil is given in Table 1.

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Declaration of Compliance according to Annex IV **Reg (EU) 10/2011** as last amended including:	**EU**
1. List of substances with restrictions (e.g. SML, Dual use additives).	
2. Confirmation that substances not included in Annex I of Reg (EU) 10/ 2011 have been assessed according to Article 19	
Compliance with **EU Regulation 1935/2004/EC**	**EU**
Compliance with **EU Regulation 2023/2006/EC**	**EU**
Statement on food allergens as listed in Annex II of Regulation (EU) No. 1169/2011 (repealing Directive 2000/13/EC with amendments) *Form issued by Tetra Pak*	**EU**
FDA 21 CFR clearance with the corresponding paragraphs	**USA**
1. Relevant sub paragraphs e.g. CFR 177.1520 (c) 2.2 for polyolefins, CFR 178.2010 and/or 178.3400 for additives, 177.1630 for film	
2. Food type and conditions of use e.g. according to table 1 and 2 of CFR §176.170	
The Safe Drinking Water and Toxic Enforcement Act of 1986. California proposition 65	**USA (California)**
A declaration of compliance covering the following **Chinese standards:**	**China**
1. **GB9685-2016**, Standard on use of additives in food contact materials and articles, including list of restricted (e.g. SML) substances	
2. **GB4806.1-2016**, General safety requirements for food contact materials and articles	
3. **GB4806.6-2016**, Plastic resin for food contact	
4. **GB4806.7-2016** Food contact plastic materials and articles with test report (only for film).	
SIL - **Substance Information List -** on substances with a special interest (e.g. substances in public debate) *Form issued by Tetra Pak*	***Tetra Pak***
CIF – **Compositional Information -** *Form issued by Tetra Pak* *Required every three years*	***Tetra Pak***
Absence of bisphenol A	**FR**

Table 1: list of main regulations requirements to fulfil by packaging in EU, USA and China

3.1.2.2 Determination of extent of migration

To guarantee compliance with the food contact legislation, migration measurements are fundamental to evaluate possible consumer risks during the use phase of the product. In this regard, two important measures are used to characterize this scenario: Overall migration (OML) and Specific migration (SML).

Overall migration (OML)

This measure defines the total mass released and transferred from a certain material towards the contained food. This parameter only takes into account the mass loss in the packaging film without distinction on nature or type. The calculation of the OML is carried out by authorized laboratories and is based on the direct contact between the material of interest and an inert liquid, "simulant" (the simulant acts as the food for the intended use). The OML is obtained in units of mg/dm^2. In order to perform the migration tests, the following information is necessary:

- The nature of the food to be in contact with the material. The (EU) No 10/2011 Regulation defines the list of simulants. For example, ethanol 10 % v/v (simulant A), acetic acid 3 % v/v (Simulant B), Ethanol 20% v/v (simulant C), etc.
- The selection of the simulant is based on a Table containing chemical finger prints of foods families in such a way that one simulant of the same nature could be chosen (EU No 10/211).

- The temperatures at which the packaging and its content are submitted (filling, sterilisation, conservation, storage, etc.) as well as the length of the processes. From this scenario, it will be possible to prepare a consistent experimental setting, according to the Regulation EU No 10/2011.

<u>*Specific Migration (SML)*</u>

This parameter gives the migration value of a particular component. Unlike the OML, the identification of the migrant is considered. Regulation (EU) No 10/2011 defines the limits of SML classifying the migrants individually and applying toxicological criteria. The SML is calculated in units of mg of the specific migrant/kg of food. The determination of this concentration is performed by two approaches:

- Laboratory analyses
- Modelling tools

Concerning the experimental procedure, the next regulatory framework is considered: “Determination of the Global Migration according to the Norm NF EN 1186”. *Reference documents:*

- *Regulation (EC) No 1935/2004*
- *Regulation (EC) 10/2011 and amendment (EC) 2020/1245*

On the other hand, different modelling tools are now used based on the availability of information regarding molecule types, product dimensionality, processing conditions, theoretical mechanisms, etc. One of this tool is known as FMECAengine. Accordingly, Table 2presents the different steps and corresponding elements collected from TERMINUS needed to carry out a modelling exercise.

FMECAengine					
PHASE	Formulation	Design	Process	Information	Mechanisms
INVENTORY	Plastic PET -Monomer -Antimonium Plastic OPP - Monomer Pastic PE/EVOH/PE - Monomer Vynil Acetate - Hexafluoropropylene - Anhydride maleic - Vynilidenfluoride - Irganox 1076 - Zinc oxide - Aluminium Adhesive Enzymes	- Multilayer - Specific adhesive layer - Fonctional barriers?	- Film production - Film storage as raw material and finished product - Assembly - Distribution - Final use	- Identification of materials - Technical and security data sheets - Regulated substances - Transformation data - Application conditions	- Diffusion through layers - Presence of enzymes - Activation of the enzyme - Simulating risk of transfer of enzyme’s sub-products
HIERARCHIZATION	- Sovents - Molecules at high concentration - Presence of methanol - Quantification - Enzymes’ residues and impurities	- Layer of direct contact - Thin layers - Chemical Stability of the functional adhesive layer?	- BPF: UE 2023/2006 HACCP? - Adhesive coating step: processing conditions (temperature, pressure) - Storage - Contamination during processing? - Activation process of the enzymes - Application of products	- Food compliance certificates of films - Declaration on composition of adhesives - Degradation products of the enzyme - Technical and security data sheets of the enzyme	- Simulation of worst case scenario of migration - Experimental trials on migration

Table 2: Different steps and corresponding elements collected from TERMINUS needed to carried out a prediction exercise

In TERMINUS, as part of the present initial integration plan, both described approaches, experimental and modelled, will be applied complementarily since current regulatory frameworks does not address the under-development TERMINUS technology.

In addition to food safety requirement, some environmental information is required to assess environmental compliance. Some related regulations are listed in the Table 3

Packaging and packaging waste directive **(PPWD) 94/62/EC**	**EU**
Raw Material Supplier Declaration on Heavy Metals and other Dangerous Substances. *Form issued by Tetra Pak*	***Tetra Pak***
Registration, Evaluation, and Authorization of Chemicals (**REACH**) *Form issued by Tetra Pak*	***Tetra Pak***

Table 3: environmental information required to assess environmental compliance

3.1.2.3 Regulation on Good Manufacturing Practices

Another key point is the **compliance with regulation on Good Manufacturing Practices**. Regulation (EC) No 2023/2006 ensures that the manufacturing process is well controlled so that the specifications for Food Contact Materials (FCM) remain in compliance with the legislation:

- Premises fit for purpose and staff awareness of critical production stages
- Documented quality assurance and quality control systems maintained at the premises, and
- Selection of suitable starting materials for the manufacturing process with a view to the safety and inertness of the final articles
- Good manufacturing rules apply to all stages in the manufacturing chain of food contact materials.

3.1.3 Collection step

In most Western- European countries, household packaging is **collected separately from paper-, residual- and organic-waste**. For the collection of special waste streams (soda bottles, batteries) local deposit systems can be in place. Consumers can return the used product or packaging for recycling. The collection of Business to Business waste is often less homogeneous. Flexible packaging needs to be successfully collected to ensure sorting, recycling and optimised quality in a circular economy. Hence, to maximize the recycling quality of all materials, (flexible) plastic packaging should be collected as a separate stream or with other light packaging and not mixed with paper, board or glass.
Typically, post-consumer packaging film waste (e.g. films, carrier bags, stretch films, wrappers, etc.) is collected from households together with other packaging materials via kerbside or co-mingled systems. It is then transported to a sorting center, where different material streams (per polymer) are defined to be later on sent to recycling facilities. It is estimated that around 62% of household and commercial PE flexible film is collected in Europe, 21% from households and 41% from the commercial stream[1].

TERMINUS project is not foreseen to directly impact this step.
Nonetheless, if we considered the situation in France and according to CITEO[2] the part of flexible packaging waste, which could be collected, will reach 310kt/y. There will be expected more quantities of plastics waste including flexible packaging collected. Today, a huge part

[1] Recycling of Flexible Plastic Packaging, Michael Niaounakis
[2] https://www.citeo.com/

a flexible packaging are not collected in the current "recycled waste stream" and are landfilled or incinerated.

3.1.4 Sorting step

This step aims to establish a first separation between recyclable materials (plastics, paper, metals…) and impurities which will be discarded to landfills and incineration facilities. In some cases, a preliminary separation is done on the main plastic resins. For example, the separation between clear and colored PET and the preparation of a polyolefin stream).

The accuracy of these sorting systems and therefore the purity of the sorted material streams has a **major impact on the available recycling opportunities and the final value of the recyclate**. The manner in which packaging waste materials are sorted can differ between member states. While one country might have a fully automated sorting infrastructure another might be more dependent on manual sorting.

Different sorting techniques for different packaging materials exist. The main technics are summarized below and in Recyclass sorting diagram described in Figure 6.

- **Plastic**: Collected plastics are sorted by type of material. If necessary, metal and beverage cartons are first taken out of the collected waste stream. Because of the many variants that exist, plastics are harder to separate and recycle than for example glass, paper, and metal. During the sorting process, very small components are removed first. Next, rigid materials are separated from large films.
- **Rigid packaging materials**: Rigid packaging materials are sorted by type of plastic: PP (trays and containers), HDPE (bottles and flasks), and PET (mainly bottles, but also trays). These sorted packaging materials are compressed into large bales and sent to a recycler.
- **Flexible packaging materials**: Large flexible packaging materials end up with the films. This material mainly consists of PE and PP.
- **Mixed stream of rigid and flexible packaging materials**: All other rigid and flexible plastics, which are recognized as plastic but are not PE, PP, or large film, are sorted in what is known as the "mixed stream." The more mono-materials the mix contains, the more it pays to sort these materials. If the mix contains a large amount of small (smaller than an A4 page) flexible packaging materials made from mono-materials, it can be worthwhile for a recycler to sort the stream first. These packaging materials can be reused in a different manner.
- **Paper and cardboard**: Many countries have an efficient collection system in place for paper, and the material is easy to recycle. However, the number of possible cycles is limited to circa four to seven, because the quality of the fibers deteriorates during each recycling process. The use of protective layers and coatings affects the paper's recyclability. B**everage cartons cannot be collected and recycled alongside paper and cardboard.** This is because such cartons contain a layer of plastic and are contaminated with organic material. In more and more countries, beverage cartons are collected and sorted separately to ensure they can be recycled as well. The beverage cartons are processed in a different factory than other paper and cardboard materials. Currently, only the fibers are recovered.
  After collection, the types of paper and cardboard are sorted by quality, from Kraft paper to newspaper. Paper and cardboard producers purchase the material based on its quality and process it to make new paper and cardboard. The smallest fibers fall through the sieves used during the recycling process and are processed to make

for example toilet paper. To preserve the paper cycle, a certain quantity of new fibers is always needed. This balance is achieved because cardboard packaging materials, which must withstand heavy loads, require longer – and therefore new – paper fibers. Solid cardboard and some types of folding cardboard can be made from shorter fibers.

- **Wood**: Wooden packaging materials can be reused or recycled, so that the material can be used for new products or packaging materials. Wooden pallets are recycled and turned into e.g. chipboard, MDF or wood chips. Wood fibers can also be used for the production of paper and cardboard.

Focus on the sorting of plastic:

In an optimal sorting center, plastic packaging is automatically sorted through a series of consecutive steps which are refining the streams (see Fig. 6) . Contamination is separated out while the material is sorted according to polymer type (and optionally, where required by colour).

In a sorting center, the separately collected packaging is first screened. The importance of screens is due to the fact that polymer types of items larger than certain sizes (typically larger than an A4 page), were more easily recognized than smaller items. The screens would separate smaller items into the mixed waste fractions. Technological developments have since made polymer recognition much more effective and efficient, allowing for more concentrated targeted streams. Therefore, the size of packaging has a decreasing impact on the final quality of the sorted waste. Screened packaging later passes through metal detection and eddy current separators, that remove any ferrous and non-ferrous metals, which constitute contamination of the waste stream.

The material then passes through wind shifters, which separate light fractions from heavier ones, and ballistic separators, which separate 2D fractions (flat items) from 3D fractions (heavy and rolling items). After these steps, the material is further refined using Near-Infrared (NIR) technology. NIR separates the LDPE film from other films and plastics in the light and 2D fractions. The rigid plastics, on the other hand, are separated into PP, PE, PET and PS streams. The material can go through more than one sorting operation or be further refined by colors and product types which means that transparent LDPE film can be separated from the colored LDPE film. Certain applications such as food contact require very high purity levels and are subject to European quality standards. In that case, the collected material undergoes several sorting and decontamination steps both in the sorting facilities, as well as in recycling plants.

Additionally, remaining materials which are sorted out during the operation are either fed back to the system to improve the material recovery or discharged and sent, along with other contaminants and impurities, to incineration plants for energy recovery.

Once the different streams are separated, sorted LDPE films are compressed and baled for transportation purposes.

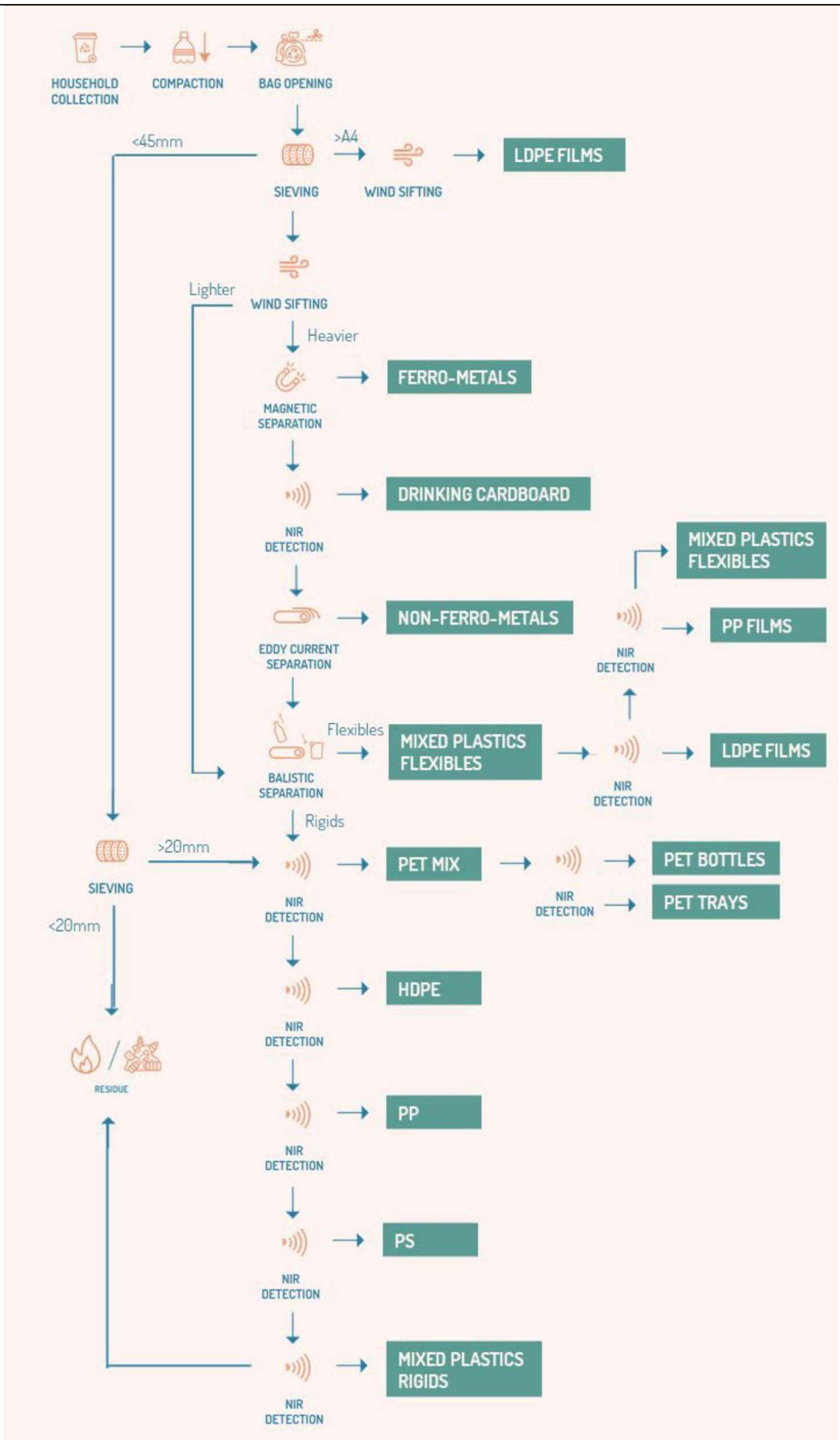

Figure 6: Sorting Methodology Diagram by Recyclass[3]

3 https://recyclass.eu/wp-content/uploads/2021/09/SORTING-EVALUATION-PROTOCOL-FOR-PLASTIC-PACKAGING_FINAL-V1.0.pdf

In France, according to CITEO the part of flexible packaging waste which could be collect 310kt/y. Only one flexible packaging waste stream is recycled today (= LDPE) The second stream (PP film) is not yet considerate as recyclable material. The third stream, including multilayers material, as targeted by TERMINUS concept, is not recyclable as well. One of the TERMINUS target would be to reach the recyclability of this ML stream (150Kt/Y).

TERMINUS project will be impacted by or will impact:
To ensure a smooth integration of the delamination unit at the recycling facilities, the following point must be addressed:

Separation of multi-layer packaging containing enzymes from the rest.

To build an economically viable system, it is essential that only packaging containing the enzymes are processed in the delamination unit. A digital watermarking can be inserted in the packaging to allow its detection and separation via the appropriate sensor (e.g. HolyGrail project). A digital water marking could be applied on the ML surface (by specific printing process using current technology). Another solution could be to introduce chemical tracers in the material. Therefore, the integration plan must foresee the integration of digital watermarking during production of the multilayer packaging and the implementation of a sorting system during the end-of-life treatment of the packaging.

3.1.5 Recyclers

Focus on the plastic streams:
Once the streams composed of plastics and papers arrive at the recycler facilities, a series of operations are performed. The materials are washed to remove some remaining impurities such as food residues.
As described in Figure 4, at the recycling plant, the waste is unbaled and additionally refined. Plastic films are further separated from other flexibles such as multilayers, black film, metallized plastics and paper labels which were not sorted out at the sorting center. This is required as the specified materials will downgrade the output material in case they pass to the melting and extrusion phase. It **must be underlined, however, that the current technologies cannot sort out all the innovations that are put on the market**. After that, the size of the waste needs to be reduced in order to pursue consecutive steps.
Shredding machines are used to grind the material into flakes, which are then sent to washing. This stage removes any remaining contamination. Friction washer which is used here has an additional in-built mechanism called a flotation tank which allows for further material separation. In a floatation tank films float while heavier materials sink. Before the material enters the extrusion stage, it is dried. In an extruder, the Plastics Films fraction is heated up to 200-220°C, melted and homogenised so that it can pass through filters to remove any impurities that cannot be melted (due to differing melting temperatures, these include: PET and PA), and then extruded into pellets.

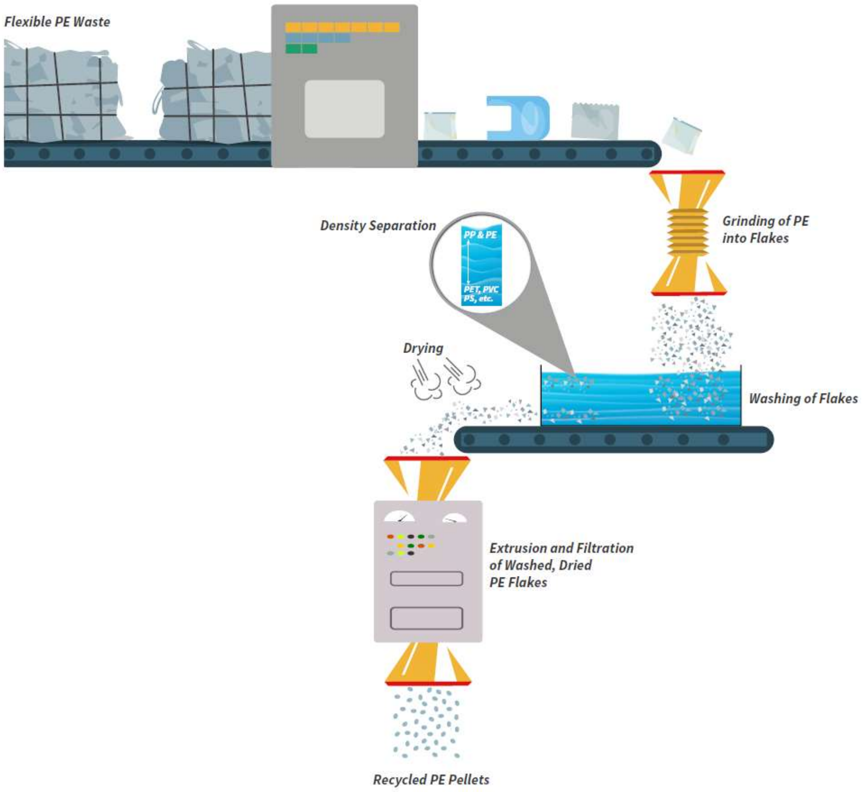

Figure 4: Simplified overview of a flexible PE recycling process

<u>TERMINUS project will be impacted by or will impact:</u>
To ensure a smooth integration of the delamination unit at the recycling facilities, the following point must be addressed:

Delamination unit

The delamination bath must be integrated after the step of separation of enzyme-containing and enzyme-free packaging. As this step is not present in the current recycling facilities, it must be added to the process. No extra full-time equivalent is foreseen to run the operation. The separated layer can then be further sorted by polymer types via NIR system. Moreover, the quality of the output material must be thoroughly checked to ensure that the delamination bath does not reduce the performance of the recycled plastic. Its quality will strongly influence the market the recycled material can re-enter and affect the economic viability of the TERMINUS technology. This unit can either be implemented at the sorting centre or at the recycling centre depending on the facilities and their country location.

3.1.6 Repulping

To be completed in the final version of the deliverable.

3.2 Needs and constraints of the process and recycling industry

To propose a technology integration roadmap, the next step is to describe the needs and constraints of the different stakeholders. Hence, depending on their position on the value chain, stakeholders will show different kinds of expectations, such as:

- **Circularity of multilayers** (Increased, quality collection and sorting): Collection schemes vary immensely across Europe, to an extent where often in one single Member State a multitude of different systems are present. Therefore, harmonized collection and sorting processes at the EU level are a must. Separate collection schemes should be implemented in all Member States to increase the quality and quantity of collected waste. In particular, collection schemes will determine the level of contamination found in the streams entering the sorting centers, and later the recycling process. Sorting can be disrupted due to excessive contamination, this will automatically lower quality and therefore the range of applications that the material could be used in. Alternatively, additional sorting steps might be required to sort out specific materials, making the process lengthier and more energy intensive. To give an example, in a household collection system where packaging is mixed with another type of waste, like organic waste, contamination presence is significantly higher. On the other hand, separately collected plastic provides for much purer streams, increasing the efficiency and decreasing the cost of subsequent reprocessing steps. Establishing separate schemes for post-consumer plastic waste and therefore creating a separate stream (including polymers like PE, PET, HDPE and PP) will lower contamination levels, increase the performance and quality of sorting centers and contribute to the production of high-quality recyclates.
  Harmonized, separate and increased collection across Europe is, therefore, a must and needs to be further supplemented with landfill ban on plastic waste and controlled waste exports. Introducing measures like standard sorting practices as well as guidelines for bales quality checks are needed in order to complement this harmonization.

- **Design for recycling for plastics films**: Properly designed, recyclable plastic packaging retains high value at the end of its useful life and can be repurposed to produce new products. Ill-designed products cause difficulties during sorting and are incompatible with recycling processes. As a consequence, this type of packaging strongly reduces the efficiency of the recycling process, its technical performance, quality of recycled material, and cost-efficiency of reprocessing. **Specific design for recycling guidelines must be followed when manufacturing a product and when introducing any kind of innovation on the market.**

- **Incineration & landfilling rates and exports in the EU28 is**:
  - a net importer of primary form LDPE/LLDPE (value of imports 20% higher than exports)
  - a net exporter of film and sheet (exports value 25% higher than Imports)

- a net importer of sacks and bags (imports 3 times the size of the Export market)[4]

The average yield of recyclate from post-consumer PE flexible films within the EU28+2 is estimated at 70% of input tonnages, suggesting around 1.8 Mt of recyclate output was therefore produced in the EU28+2 (1.3 Mt from post-consumer flexible films and 0.5 Mt from production scrap). The non-recyclable fraction due to the design constraints presented above is being sent to incineration or landfill depending on the country's location.

- **Compliance to legislation that add Cost / taxes / fees** to the material and that could promote the way of ML flexible films including an innovative recycling solution as TERMINUS (against ML packaging not recyclable).

- **Integration of technology in waste treatment infrastructures**: The TERMINUS technology should be implemented alongside the existing processes at the current sorting and recycling facilities. This will benefit a smooth integration of the new processes and an economically viable process. Therefore, **it is of high importance that the new processes work in symbiosis with the current process scheme**.

- **Competitive technologies**: Nowadays, the recycling processes are quite always non-environmental friendly because it is hard to reach layers' delamination. Processes involve mainly chemicals (carboxylic acids notably) to achieve either dissolution of some of the layers or physico-chemical delamination by diffusion of the reactant in the tie layer (SAPERATEC). Of course, wastes are crushed to increase the accessible area for solvation or diffusion of the chemicals. As mainly multi-layers are polyolefin based, solvents must be unsafe aromatics (xylene, benzene). In the case of Some industrial processes and technologies are currently being developed to improve recyclability of multi-layers.
  The REFLEX project (international consortium with major stakeholders: DOW, Unilever…, ended in 2016) studied the recyclability of PET/PE and PA/PE laminates. An inhomogeneous mix was observed, preventing their reuse. It is therefore not fulfilling the main principles of circular economy principles.
  The ENVAL process recycles aluminium from multi-layer packaging, through polymers pyrolysis. Plastics can only be recovered into a degraded form, additionally, this technology is costly, time-consuming, and requires an undesirable amount of energy to achieve the separation of the individual components. The Creasolv project carried out by the Fraunhofer institute extracts target polymers through organic solvents, based on Hansen solubility parameters. It does not yet recycle multi-layer packaging. The SHERPACK project is currently involved in recyclable paper-based packaging. The LIFE rPack2L project in progress studies a flexible packaging delamination solution specifically for PVC/PET-based multi-layer films. The Wheylayer project is built on the development of a protein-based adhesive to process high barrier biopolymers multi-layers. Delamination proceeds ex-situ by washing and dipping the multi-layer material in a specific enzyme containing medium.

[4] https://www.plasticsrecyclers.eu/_files/ugd/dda42a_ff8049bc82bd408faee0d2ba4a148693.pdf

The TPPS patent of 1996 described a multi-layer packing comprising polyvinyl alcohol or other water-soluble, thermoplastic resin layers disposed on both sides of a paperboard base material layer, and other thermoplastic synthetic resin layers laminated thereon. An aluminium foil layer may also be provided over a polyolefin adhesive resin layer and a fast separation of the components and a low-fibre content in the resins can be achieved.

During the METEOR-PLAST project, IPC studied recycling of blend of PP, PE and PS coming from rigid packaging of post-consumer wastes. The aim of the project was to optimize the blend morphology by means of an elongational flow reactor (Meteor). The project highlighted an improvement of the mix morphology and the mechanical properties of the material. Blend based on PE/EVOH coming from multi-layer packaging are currently investigated by IPC using Meteor technology.

Finally, the CARBIOS technology propose the enzymatic degradation of PET material. A close monitoring of this technology is realized in the frame of the project.

- **Legislation and Food contact**: to be used in new packaging application, a recyclate must comply with several requirements as described in the regulation on plastics materials and articles intended to come in contact with food (10/2011) and the regulation on recycled plastic materials and articles intended to come into contact with food (282/2008). A recycling process must demonstrate the removal efficiency for specific contaminants that could be present in the input material. The results of the test must be put in the form of an application to the European Food Safety Authority (EFSA), which will develop an opinion based on the presented data. Subsequently, the European Commission can provide authorization for the processes based on such EFSA Opinions. **The legislation on food contact must be closely monitored to ensure that the processes developed in the TERMINUS project will still be compliant with the upcoming revision of those regulations**.

- **Legislation on waste**: Packaging and Packaging Waste Directive (94/62/EC) covers all packaging placed on the market in the Community and all packaging waste. It **requires the return and/or collection of used packaging in order to meet targets for the recovery and recycling of this material**. This includes plastic packaging and plastic packaging waste. A target of 22.5% for the return and/or collection of plastic materials contained in packaging were to be attained by no later than 31 December 2008. Although the target dates have passed, amendment 2005/20/EC set different target deadlines until the end of 2012 for ten Member States (the Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Slovenia and Slovakia). Commission Decision 1999/177/EC established a derogation for plastic crates and plastic pallets in relation to heavy metal concentration levels established in the Directive on Packaging and Packaging Waste. In 2009, the Commission extended this derogation however it is now under review and it is uncertain whether it will be extended. If this derogation is not continued it will affect recyclers, bottlers and brand owners as the current methods for disposal and recycling of plastic crates and pallets may become illegal.

Plastic materials and articles intended to come into contact with food Directive (2002/72/EC & 2008/282/EC) relating to plastic materials and articles intended to come into contact with food, **establishes a list of monomers and other substances such as additives, that are permitted for use in the manufacture of food**

packaging. It also amends existing restrictions, in particular related to epoxidised soybean oil (ESBO) migration in PVC gaskets used to seal glass jars containing foods for infants and young children. On 28th March 2008, the Regulation 282/2008/EC allowing the use of recycled plastics for food contact applications was published in the Official Journal of the European Union and entered into force on the 20th day following this publication. The regulation organizes a transition period during which applications for authorization of a recycling process shall be submitted to and evaluated by the European Food Safety Authority (EFSA). Only when all the recycling processes for which an application has been submitted during the 18 months following the publication of the EFSA guideline on the 21st May 2008 will have been evaluated by the EFSA, the Commission shall within six months draft the decisions granting or refusing authorization of the recycling process.

4 Processing of multilayer packaging with TERMINUS : Overview of the current production and recycling processes integrating TERMINUS

4.1 Summary of the TERMINUS concept

Packaging multi-layer plastics show poor recyclability as no efficient solution exists to properly and safely separate each layer. Yet, each layer must have a purity over 95% w/w to be reusable (this purity must be reached to maintain acceptable properties). Multi-layer materials are composed of barrier, printing-ink and heat-seal (PE) layers and adhesive to hold them in lamination processes. Materials to recover are functional layers (e.g. PE, PP, PA, PET). The project concept is to enable the separation of multi-layer plastic packaging through triggered enzymatic degradation of adhesives and tie layers. The feasibility of this main concept relies on several approaches:

1. **Developing new smart multi-layer materials with triggered biodegradability**. We will design and develop multi-layer systems containing enzymes that can resist to material processing and can be activated only at the product end of life. 95% of adhesives used in the manufacturing of multi-layers are PUR based. This polymer is degradable by enzymatic activity. PUR adhesives and tie layers for blown extrusion will be optimised (formulation, components) to maximise degradability. Inclusion of enzymes represents a major innovation in the field for plastic processing.
2. **Study of enzymes to select the most performing and resistant ones for biodegradation.** Extracellular extremozymes from desert-dwelling bacteria (adapted to high UV, heat and low water activity environment) or commercially available enzymes will be analyzed and adjusted in order to identify their ability to resist harsh conditions and ensure biodegradation. Besides, the use of enzymes for the degradation avoids the use of harmful chemicals, and solvents. Materials of interest are not degraded upon triggering. Associated with document Ref. Ares(2018)6181549 - 03/12/2018 814400-2 - TERMINUS Part B 10
3. **Increasing enzymes thermal resistance through protection**. Highly promising techniques to protect enzymes against temperatures compatible with adhesive lamination (50°C during 30-60min for Solvent Free adhesive lamination and 80°C during 5-10sec for solvent based adhesive lamination, blown extrusion (120-180°C for up to 3 min) and even extrusion coating lamination are available at TRL 3, e.g. organosilica layer. These techniques will be essential to retain functional enzymes after manufacturing processes and use of these multi-layer plastic materials.
4. **Triggering enzymes activity at the right moment in sorting centres**. Smart techniques to trigger the activity of enzymes by UV radiations, cyclodextrins or water solutions containing exchangeable anions are available, enabling the release of redox mediators or enzymes after shredding/perforation. These techniques, currently developed in laboratories, must be optimized to meet requirements of sorting/recycling centres.
5. **Manufacturing smart multi-layer packaging through state-of-the-art methods to ensure their processability by industrials**. Developing polymers that have the required processing and packaging performance and that can be biodegraded by enzymes would be a major innovation in the packaging sector. This manufacturing must prove that protected enzymes can be processed through current plastic processing conditions. Process optimisations will be necessary. We will prove the

compatibility with printing processes and storage conditions. End-users will manufacture industrial demonstrators.

6. **Reusing multi-layer packaging after each layer purity is assessed, according to circular economy principles**. Biodegradable bio-based polymers such as PPC, PLA, PBS and ε-PCL have a strong potential as tie layer in blown extrusion due to relatively low processing temperatures (notably 90°C for ε-PCL, 115°C for PBS). Enzymatic degradation of layers must also be considered for the recycling by design of multi-layers. All potential obstacles, bottlenecks that could hamper the fast implementation of the TERMINUS project will be evaluated and solutions/recommendations proposed: fulfilment of standard requirements (e.g. food contact, recovery and recycling of plastic waste), consumers' acceptance and involvement, risks and opportunities of national and EU legislations, integration into existing recycling schemes (collect and sort enzyme-containing packaging: e.g. using printing or novel technologies such as digital watermarking), obstacles to the replication of the TERMINUS process chain, economic assessment (collection schemes, available quantities, profitability of plants, CAPEX, OPEX).

4.2 TERMINUS original approach of packaging multilayer valorization

The existing approaches attempting to tackle the problem of the end-of-life treatment of multilayer packaging present a series of significant and varied constraints which prevents an efficient implementation. Among these difficulties we find, **in general, poor eco-friendly delamination methods because of the use of large amounts of solvents or dangerous chemicals, letting alone the high cost involved; too punctual solutions where only the recovery of specific materials are targeted; low added value bulk treatments.** Furthermore, all the procedures targeting the separation of layers are characterized by a completely downstream treatment of the multilayer packaging wastes with respect to its cradle to end of life treatment timeline. This increases the difficulty to envisage efficient solutions since the latter will depend on efforts coming only from an external set of conditions.

TERMINUS proposes an end-of-life solution for multilayer films conceived from the formulation (intrinsic approach) of the functional layer: the adhesive element. To this end, selected enzymes will be integrated to the adhesives and/or tie layers prior to processing in order to be activated during the waste treatment step. In this way, the biodegradation activity into the adhesive layers will allow for the constituents films to be detached and then recovered and sent into the mechanical recycling chain. The Figure 5 schematically describes the main steps configuring the TERMINUS strategy.

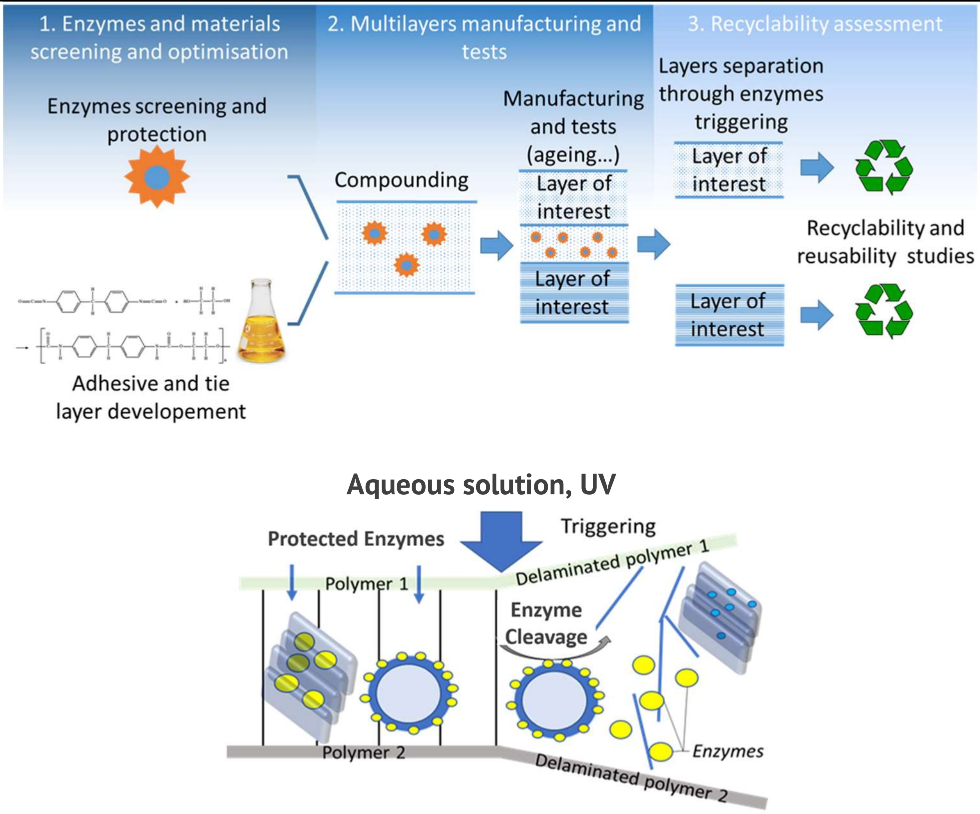

Figure 5: Schematic representation of the key steps of TERMINUS strategy and innovation. Upper: main phases, lower: key film separation phase by triggering and enzymes' release.

After a careful enzymes screening, the selected ones will be encapsulated and/or transported by an inorganic carrier, allowing to disperse them into the adhesives. A triggering system consisting of salt-based solution will give place to the release of the enzymes, which will in time begin the biodegradation process.

4.3 Key milestones for successful integration

From the different points identified in the previous paragraphs, several of them were identified as essential, and shall be addressed in priority to ensure proper integration of the TERMINUS technology by the market. Hence, the **following points are identified as key milestones**:

- Economic competitiveness during manufacture (& entire process)
- Legislative and regulation compliance (e.g. food contact and environment, see D2.2 Chapter II p 16)
- Integration in sorting infrastructure (marking of packaging to allow for its recognition). Possibility to **detect multilayer packaging with the sorting systems already installed at the recycler facility**.
- Triggered delamination
- Integration in recycling infrastructure (permits, PPE/safety, etc.)
- Uptake of materials in new articles and quality of the produced plastic
- Quality control management systems in place
- **Qualities of the enzymes** with different properties. Creation of a value chain for the enzymes. Identification of possible enzymes providers. Which storage condition?

Quality of the dispersion (need of an extra mixing step). Stability is still an issue, who is mixing the adhesive?

The following Figures describe, on one hand, the key integration points of the ML manufacturing steps into the value chain of packaging production. On the other hand, the technology developed by TERMINUS concerning the film separation of multilayer wastes is, in turn, also placed into the recycling chain as a first technical approximation of its valorization.

In general lines, Figure 6 presents a first approximation of the technical key points to be revisited during the integration of TERMINUS in the manufacturing of packaging multilayers by adhesive lamination. What is to be highlighted in the first place is the potential dependency of this technology on a brand-new value chain of production of enzyme-containing adhesives. Enzyme's production, protection and integration into adhesives are the main phases constituting this value chain. Once integrated the enzyme-containing adhesive as raw material, further impact analysis in the different technical, logistic and product quality key points is suggested in Figure 8.

Moreover, Figure 7 depicts the same type of approximation, as described above, for the food packaging multilayer elaboration by blown co-extrusion. In this, unlike adhesive lamination, the main TERMINUS impact about raw materials is based only on the supply of enzymes, or enzyme-carrier filler by stakeholders, since the compounding steps may be carried out by the processors. Further impacts in some other specific technical and logistic areas are also suggested in the Figure.

Finally, in Figure 8, a noteworthy remark has to be done for the technology of coating extrusion lamination. In this case, the TERMINUS integration lies in the supply of raw materials as semi-finished multilayered products from, on one hand, adhesive lamination and, on the other hand, blown co-extrusion multilayer lamination. Both are indicated in the blue squares. From this starting point, impacts or repercussions on processing would turn out to be more absorbed, in principle, by the existing methodology but, as for the other technologies, a more exhausting analysis of the key points will be developed.

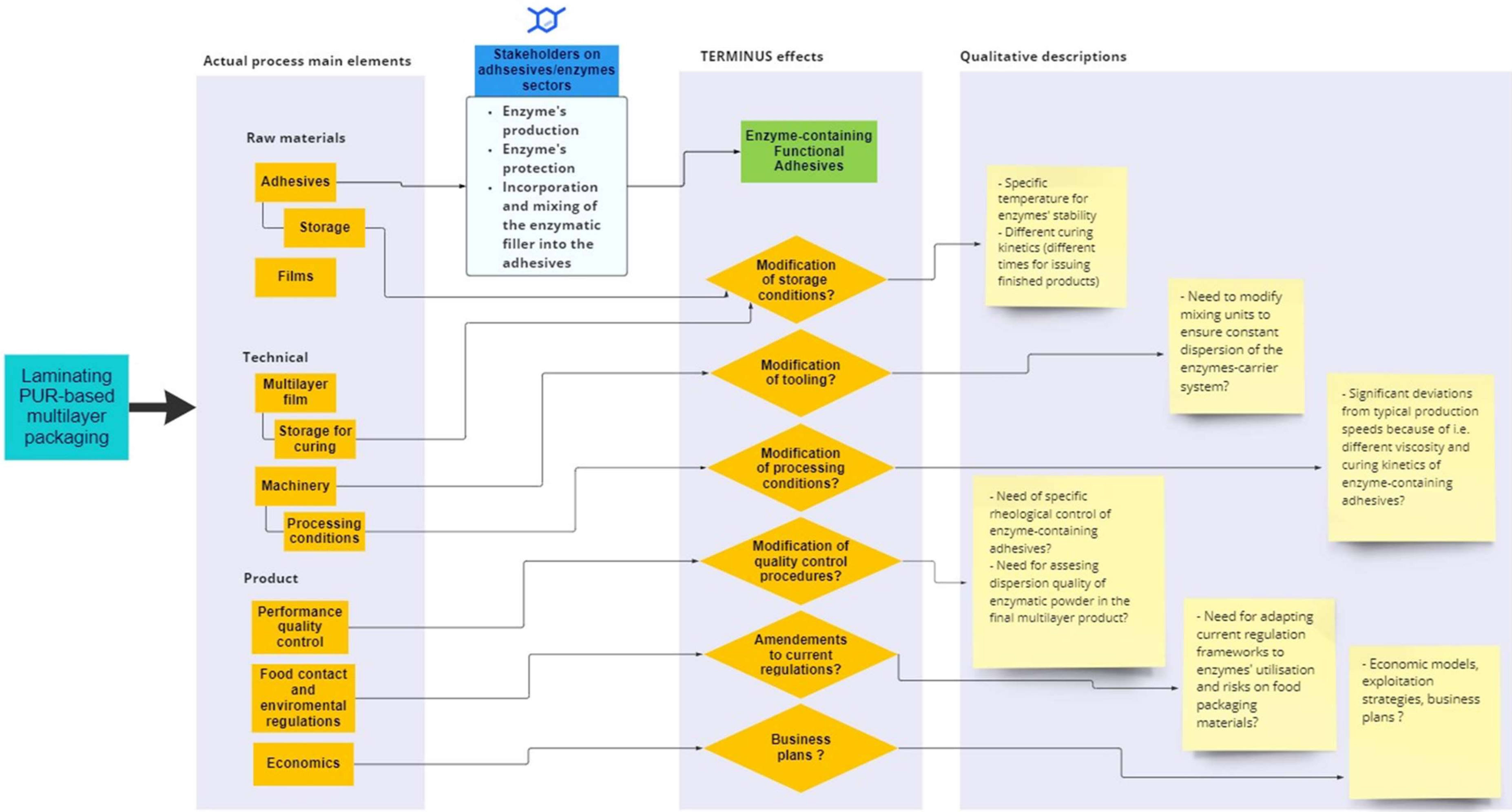

Figure 6: key integration points of the ML manufacturing steps into the value chain of packaging production by PUR-based Laminating Process

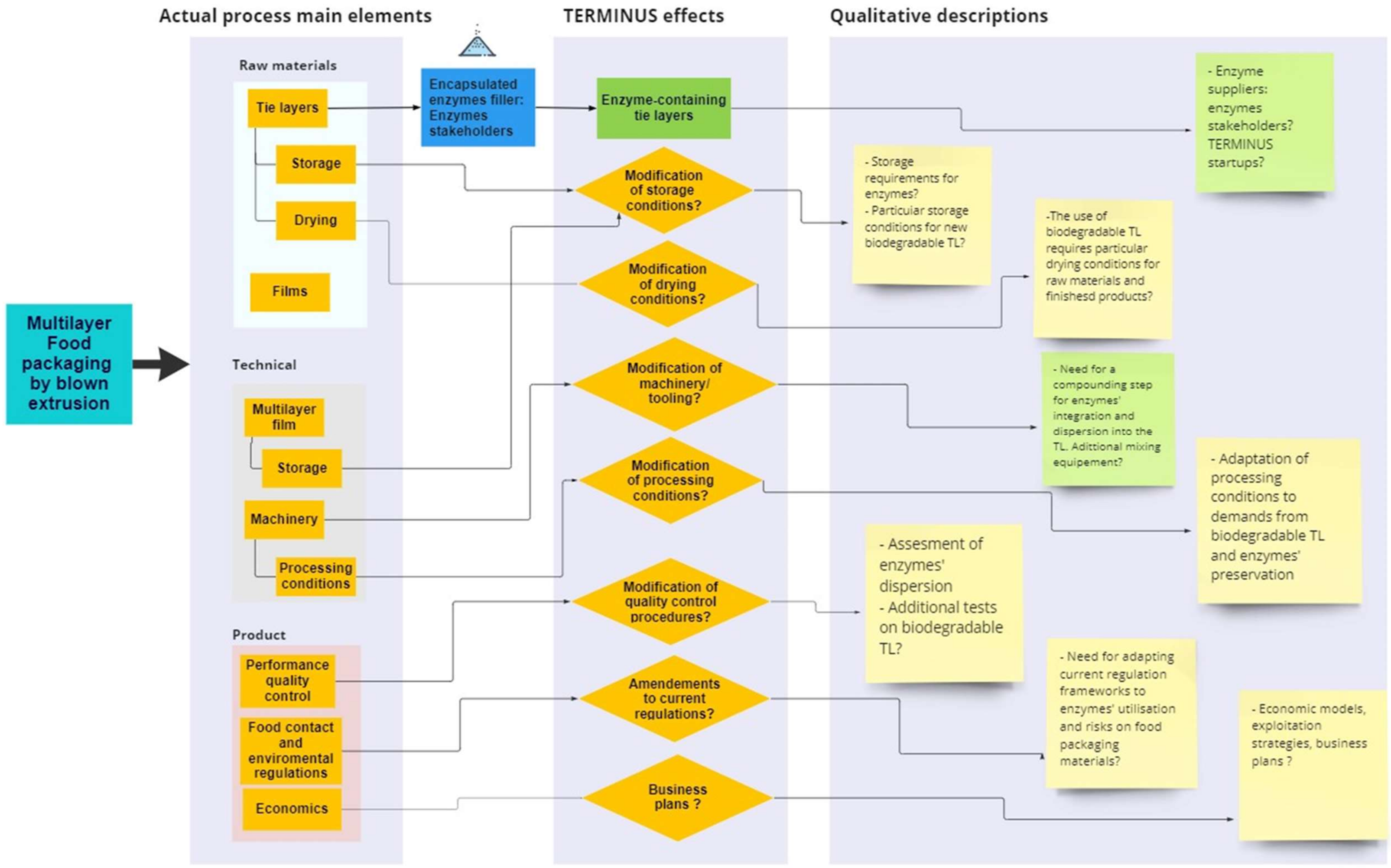

Figure 7: key integration points of the ML manufacturing steps into the value chain of packaging production by Blown Extrusion laminating

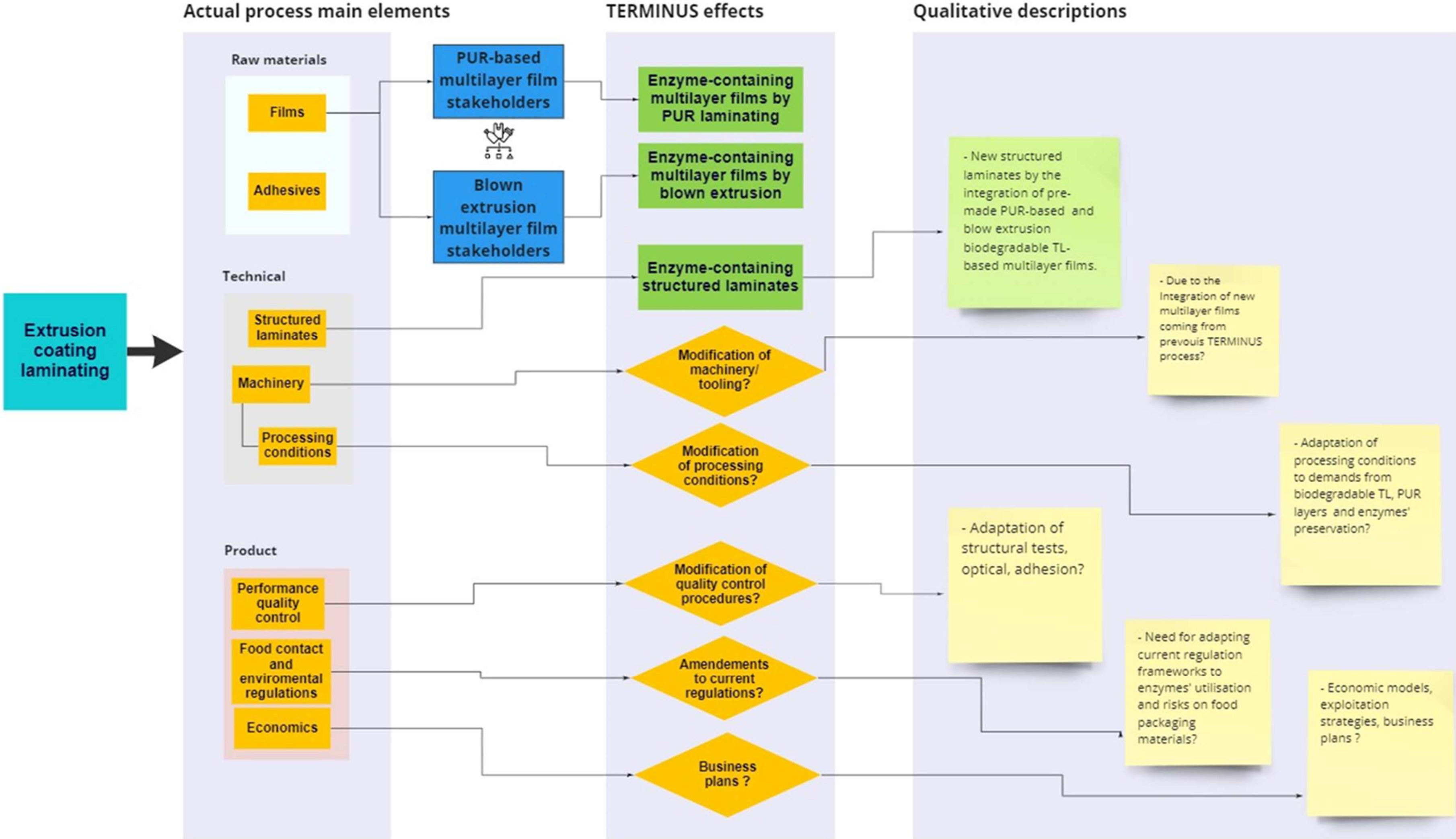

Figure 8: key integration points of the ML manufacturing steps into the value chain of packaging production by Extrusion Coating Laminating

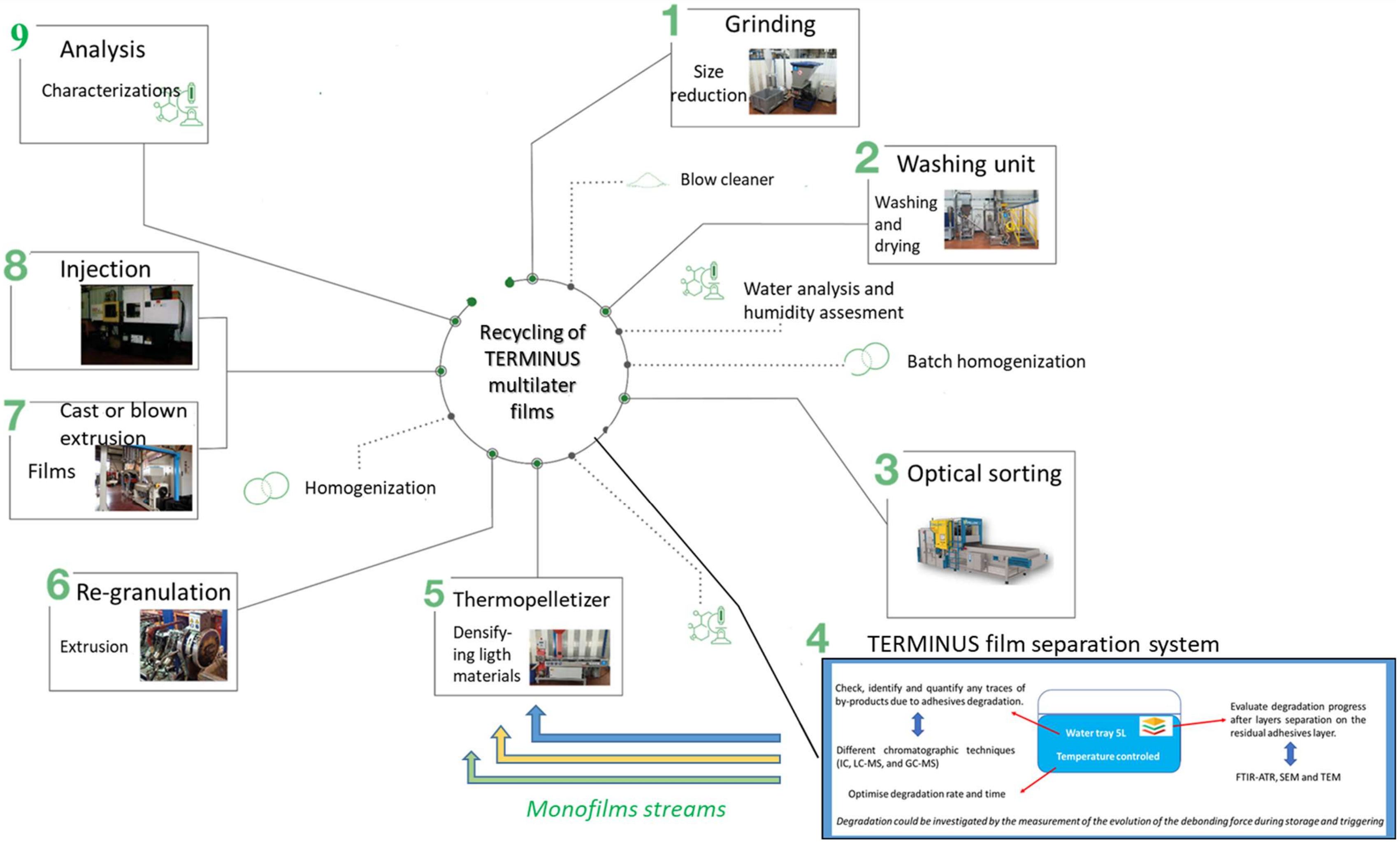

Figure 9: key integration points of the ML recycling steps showing the insertion of the novel film separation technology developed by TERMINUS

In Figure 9, the main elements of a recycling chain for flexible films are shown. As stated for the TERMINUS scope, the central strategy of the project has as a departing point the efficient separation of the films constituents of a multilayer packaging structure. As such, the central interest of TERMINUS is to assess the recyclability of mono-films issued from an innovative separation device. The latter, however, may subject the material to important chemical phenomena given the presence of degradation products result of the enzymatic attack. In this sense, strong attention is given so far to the recycling chain beyond sorting operations, involved with the multilayer selection, which is not in the direct scope of TERMINUS. Nevertheless, Figure 9 intends to depict the TERMINUS separation technology into a general view of the existing recycling technology.

5. Technology integration action plan

The technology integration plan will be developed in detail based on the key milestones identified in the document and will also follow the structure described in Table 4.

Who ?	What ?	How ?
Production industries	Integrate TERMINUS technology within the process of multilayers	Comply to all specifications of current ML: Quality, enzyme quality and mixing, food contact, safety, economic aspect…
Sorting industries	Detect only the ML including TERMINUS Technology	Water marking, other detection tool, quality of the delamination…
Recyclers industries (NEW)	After the general sorting step, a specific bales of ML enzymes-containing have to be treated by the delamination device.	After this step, we will have different kind of plastics which will have to be separated again, and maybe washed. Then, recyclers industries will be able to recycle mono-layers of films according to their know-how and current process in place.
Recyclers industries	Delaminate and recycle each mono layers films	Integrate the new recycling technology (Prototype device from WP6)
	Sell Recycled material from TERMINUS Tech	Make a recycled material in compliance with all specifications : Quality, economics aspects…

Table 4: structure of the TERMINUS project technology integration plan

6. Conclusion and next steps

Deliverable D8.7 is the initial version of the technology integration plan that proposes a strategy to integrate the project outputs within the current structures of the packaging and recycling industries.

The deliverable includes a methodology especially designed by the consortium to address this road mapping. The methodology was supported by the following steps:

- **Overview of key steps** of the current production and end-of-life management process.
- **Identification of the needs and constraints** from multilayers packaging manufacturers, sorting and recycling centers.
- **Identification of all the elements inside this value chain that will be impacted** by the TERMINUS technology.
- **Identification of external elements** that will impact the TERMINUS technology.
- A deeper description of the **key integration points** and how the project will be impacted by those elements and how it shall adapt.

Hence, several key integration points were identified as essential, and planned to be addressed as a priority to ensure proper integration of the TERMINUS technology by the market. The **following key integration points were identified as key milestones**:

- Economic competitiveness during manufacture (& entire process)
- Legislative and regulation compliance (e.g. food contact and environment, see D2.2 Chapter II p 16)
- Integration in sorting infrastructure (marking of packaging to allow for its recognition). Possibility to **detect multilayer packaging with the sorting systems already installed at the recycler facility**.
- Triggered delamination
- Integration in recycling infrastructure (permits, PPE/safety, etc.)
- Uptake of materials in new articles and quality of the produced plastic
- Quality control management systems in place
- **Qualities of the enzymes** with different properties.

This set of milestones was proposed to pave the way for a future integration action plan. In the next and last version of the technology integration plan, those key points will be detailed as well as the update of the whole document following the technical progress of the project.

The repulping value chain will be added into the final version of the deliverable.