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Carolina Mejia, MONDRAGON Corporation

FORE-
WORD

SHARING KNOWLEDGE TO DRIVE SUSTAINABLE PLASTIC RECYCLING

The PRIMUS Best Practice Book represents the culmination of our collective efforts and learnings in advancing plastic recycling for the automotive and home appliance sectors. This book is not merely a technical guide but a reflection of the journey we have undertaken in striving to improve the quality, sustainability, and circularity of recycled polymers.

Throughout the project, we encountered both successes and challenges. By sharing our best practices as well as the obstacles we faced, we aim to provide valuable insights that can inspire others to adopt, adapt, and improve upon these practices in their own operations. From ensuring compliance with legislation and managing sustainable supply chains to innovating in mechanical recycling processes, this book offers a comprehensive exploration of the various facets of plastic recycling.

In addition to technical advancements, this book highlights the importance of engaging society in recycling efforts, offering perspectives on public perception and gender dynamics in plastic recycling. Our hope is that the lessons captured here will not only serve as a resource for stakeholders but also foster broader collaboration and innovation in the field of recycling.

We are proud to share the knowledge and experiences gained through PRIMUS, and we look forward to seeing how these insights can help shape a more sustainable future for plastics.

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OUR COORDINATOR´S THOUGHTS

Jani Pelto, VTT

COORDI-
NATOR´S
LEARNINGS

As the coordinator of PRIMUS, I must admit that due to my personal plastics engineering background it is easy to forget the many different and truly relevant viewing angles one can have on the topic of plastics recycling. Let us take the business perspective as an example: making a technical part with WEEE plastics for home appliances or the automotive industry is currently perhaps NOT a great business. Why is that? In my plastics engineering perspective, the world looks almost ready.

We have seen in this PRIMUS project and several times in many other projects that there are no big technology gaps that prevent us from building at least great demonstrations and sustainable business around recycled plastics. Also, according to the consumer and stakeholder studies we have made in PRIMUS the public acceptance on recycled plastics exists. The main issue is still the limited availability of suitable waste feedstocks in large quantities and in reliable streams, and of course the fluctuations in the quality of the recyclates that we can produce from variable feedstocks. These issues we have been dealing with in PRIMUS and some of our findings are now being introduced in this Best Practice Book. Enjoy your reading!

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Carolina Mejia, MONDRAGON Corporation

INTRO-DUCTION

The primary goal of PRIMUS is to improve the quality and sustainability of recycled plastics. This is achieved through a combination of technical innovations, the development of robust methodologies for sustainability assessments, and the integration of these practices across the supply chain.

The PRIMUS Best Practice Book is a comprehensive resource designed to share the insights, methodologies, and outcomes of the PRIMUS project, which aims to advance the recycling of plastics in the automotive and home appliance sectors. With an increasing global push towards sustainability, the project explores ways to improve the recycling process, enhance the quality of recycled plastics, and ensure that these materials meet stringent environmental and health standards. By leveraging new technologies, methodologies, and stakeholder collaboration, PRIMUS has developed best (and worst) practices to address the challenges of plastic recycling and circular economy integration.

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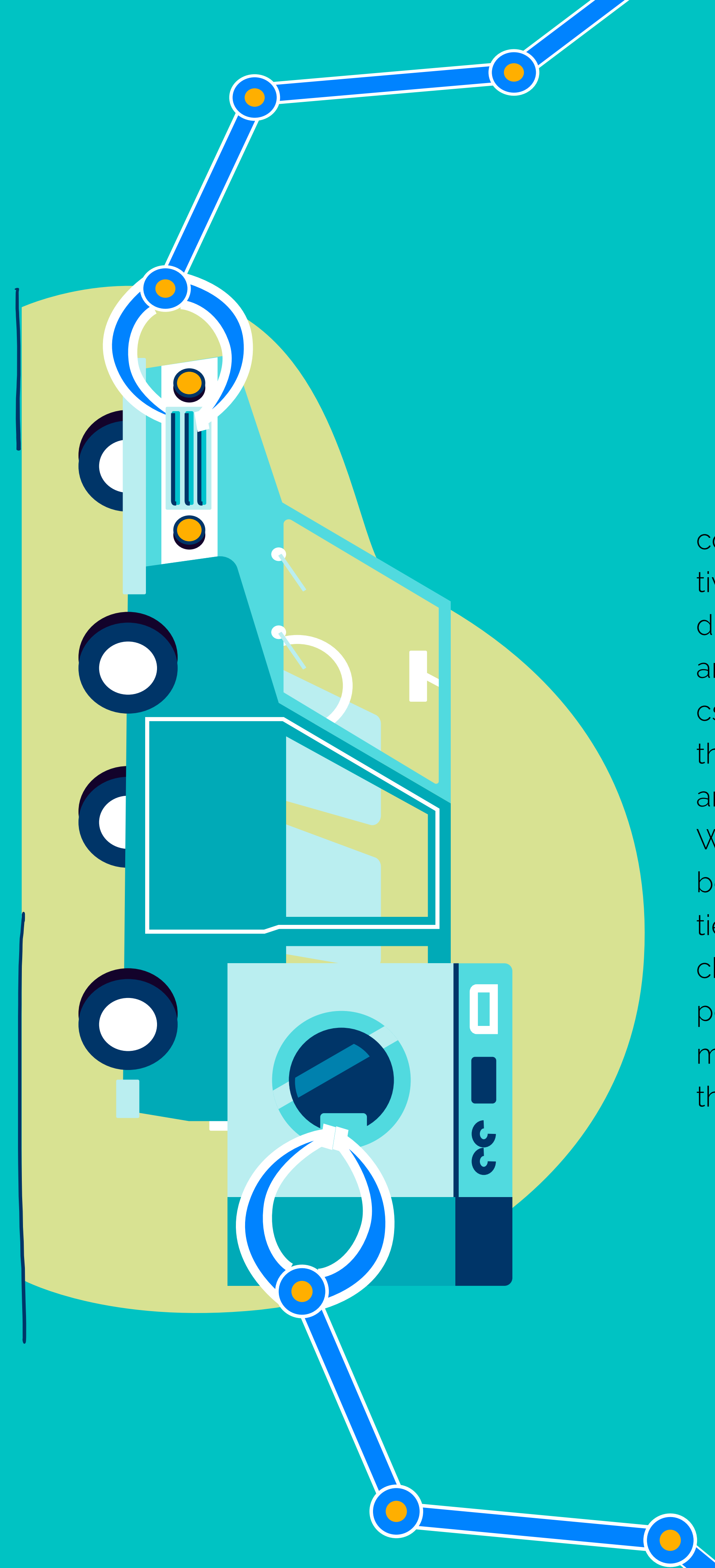
INTRODUCTION

Background and Current Situation

Jani Pelto, VTT

As the petrochemical industry offers excellent quality primary plastics with an extremely competitive price, there is currently no real driver for boosting the recycling of plastics. It is not that the industries didn't already consider this or somehow missed the opportunity to take the recycled technical plastics into their production lines. It is just that the risk and effort versus gain have not met yet. The automotive sector, for example, will continue using only primary plastics as long as there is no real gain in changing to (partially) recycled material. However, the situation might change rapidly. Already new EU-regulations are in force on recycled



content in plastics packaging (PPWR directive) and there are new updates on the end-of-waste criteria for plastics. Upcoming are requirements from the EU wide plastics policy framework (timeline unknown) on the recycling of end-of-life-vehicles (ELV) and the recycled content in automotives. We trust that the upcoming legislations will boost the investments in recycling facilities and new collection points for non-packaging technical plastics (ABS, PC, HIPS, polyamides) in the future. This will produce more volume and hence more security to the supply chains.

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Objectives and Approach

Jani Pelto, VTT

The high-quality standards of original equipment manufacturer (OEM) of household appliances and automotive components and the related safety issues will be best dealt by transparent product quality certification systems and openly available sustainability and Life Cycle Assessment (LCA) data for non--expert sustainability "practitioner", that is for us people that design the plastics parts and appliances. Building trust across the value chain from recyclers to their customers and end-users will require more standardized ways to ensure quality and safety of recyclates from WEEE. This can be enabled by sampling and testing already at the recycling facility, and more information in the technical datasheets of the final formulation. It is fair to say that for a wider use of WEEE plastics, supply chains will need to be benign and economically feasible with larger industrial scale (emerging) de-contamination processes to deal with hazardous substances.

In PRIMUS, we have specifically focused on the removal of brominated flame retardants from ABS and HIPS. Indeed, there are general challenges in reliable sampling, detection and removal of halogenated flame retardants and other potentially hazardous contaminants from the plastics. New EU wide safety standards and some new restrictions regarding the residual levels on persistent organic pollutants (POPs) and other REACH regulated compounds are currently planned in the EU. The final plastic formulations with high recycled content are best made using advanced inline controlled compounding lines generating product data "in flight" during the process. Such data can relate to the volatile organic content (VOC) level, colour, or the processability of the material, for example. These are all topics which we have touched and brought together in the PRIMUS concept, and which we have also described in some detail in this book.

Audience

Julia Cilleruelo Palomero, GreenDelta

This book collects the work of the PRIMUS project on the innovation of plastic recycling and its application, including traceability, social and environmental sustainability assessments.

Recyclers and related researchers will benefit from reading section 4, dedicated to process innovation in recycling and characterisation.

Both recyclers and plastic part manufacturers can find interesting section 3.1 about legislation, 3.4 about traceability systems and digital product passport, 3.5 about a developed "quality-quantity match model", and consequently the practical application of the research in section 5 with the demonstrator cases. Section 6 about consumer acceptance and engagement is most probably also interesting for this audience.

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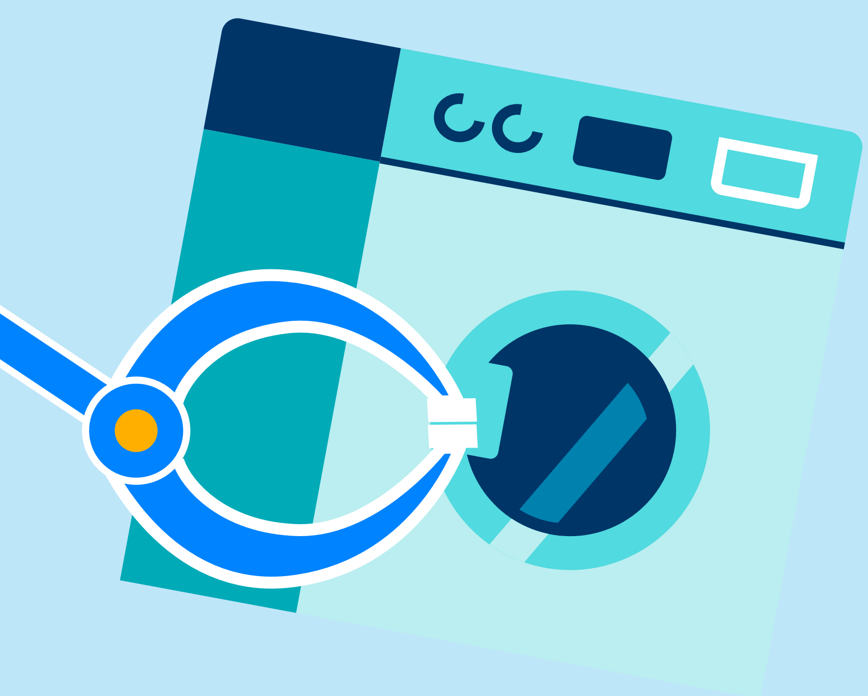
INTRODUCTION

Those interested in answers about recycled plastic sustainability can read about the developed sustainability methodology and datasets in section 3.2 and 3.3, followed by the sustainability assessment of the demonstrator cases throughout in section 5. Consumer acceptance and engagement in section 6 is most probably also of interest.



Consortium

Carolina Mejia, MONDRAGON Corporation

The PRIMUS consortium, with 10 partners and 2 affiliated entities, exemplifies a well-balanced, interdisciplinary collaboration that merges technological expertise, industry insight, and market-driven approaches. With a robust combination of internationally recognized research institutions, universities, industrial leaders, recyclers, and SMEs, the project benefits from a strong network of expertise that ensures the successful execution of its ambitious yet realistic work plan.

A key strength of PRIMUS lies in its ability to integrate innovation across the entire plastic recycling value chain. The consortium members specialize in various complementary fields, including the development of novel and safe dehalogenation pre-treatment technologies (University of Eastern Finland, VTT), assessment and offset of polymer degradation (VTT, University of Eastern Finland), advanced sampling and characterization methods (University of Eastern Finland, Plastic Recyclers Europe), and cutting-edge recycling technologies (VTT, Cikautxo, Cikatek, MTC). Furthermore, digital traceability and information management solutions (Circularise) enhance the transparency and efficiency of the recycling process, while sustainability assessments (GreenDelta) and value-added applications (Cikautxo, Cikatek, Maier, MTC, VTT, Coolrec) drive the market readiness of recycled materials. Crucially, PRIMUS also prioritizes the economic and regulatory aspects of recyclate market uptake (Plastic Recyclers Europe, MONDRAGON Corporation) and incorporates social sciences and humanities perspectives (Tallinn University) to ensure a holistic approach.

The consortium's dynamic collaboration has already yielded notable advancements, particularly in the integration of recycled polymers into industrial applications. By addressing critical challenges such as mechanical performance, chemical compliance, and aesthetic requirements, PRIMUS partners enable the development of high-quality recyclates tailored to meet industry needs.

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rPOLYMER SUPPLY CHAIN MANAGE-MENT:

Quality Assurance and Sustainability

1 Registration, Evaluation, Authorization, and Restriction of Chemicals.
2 Persistent Organic Pollutants
3 Restriction of Hazardous Substances
4 Candidate List of substances of very high concern for Authorisation - ECHA

Compliance with product legislation

Mathilde Taveau, Plastics Recyclers Europe

1. LEGISLATIVE BACKGROUND

Recyclers must ensure that products made from waste meet product regulations and "end-of-waste" criteria under the Waste Framework Directive, which requires strict monitoring of certain chemicals, or Substances of Concern (SoCs). These SoC include substances regulated by REACH[1], POPs regulation[2] and the RoHS Directive[3] . Recyclers must inform customers if a Substance of Very High Concern (SVHC)[4] exceeds regulatory limits and determine whether additional regulatory measures apply. Given the complexity and cost of analysing over 300 regulated substances, the PRE-1000 industry standard was developed to be an efficient screening method to enable compliance, reducing the need for extensive laboratory testing.

2. PRE-1000 KEY PILLARS

Product Definition: products are categorized by their input waste type and polymer composition.
Sampling and Sample Preparation: extruded plaques made of recycled pellets are to be employed for the analysis to ensure consistent, homogeneous samples.
Substance Screening Tool: The tool uses an exclusion-based approach by cross-referencing a comprehensive, regularly updated list of SoC and substance-specific parameters such as physical-chemical properties, technical function, additivation rate, polymer specificity, and historical use. If substances cannot be excluded, recyclers should apply analytical methods:

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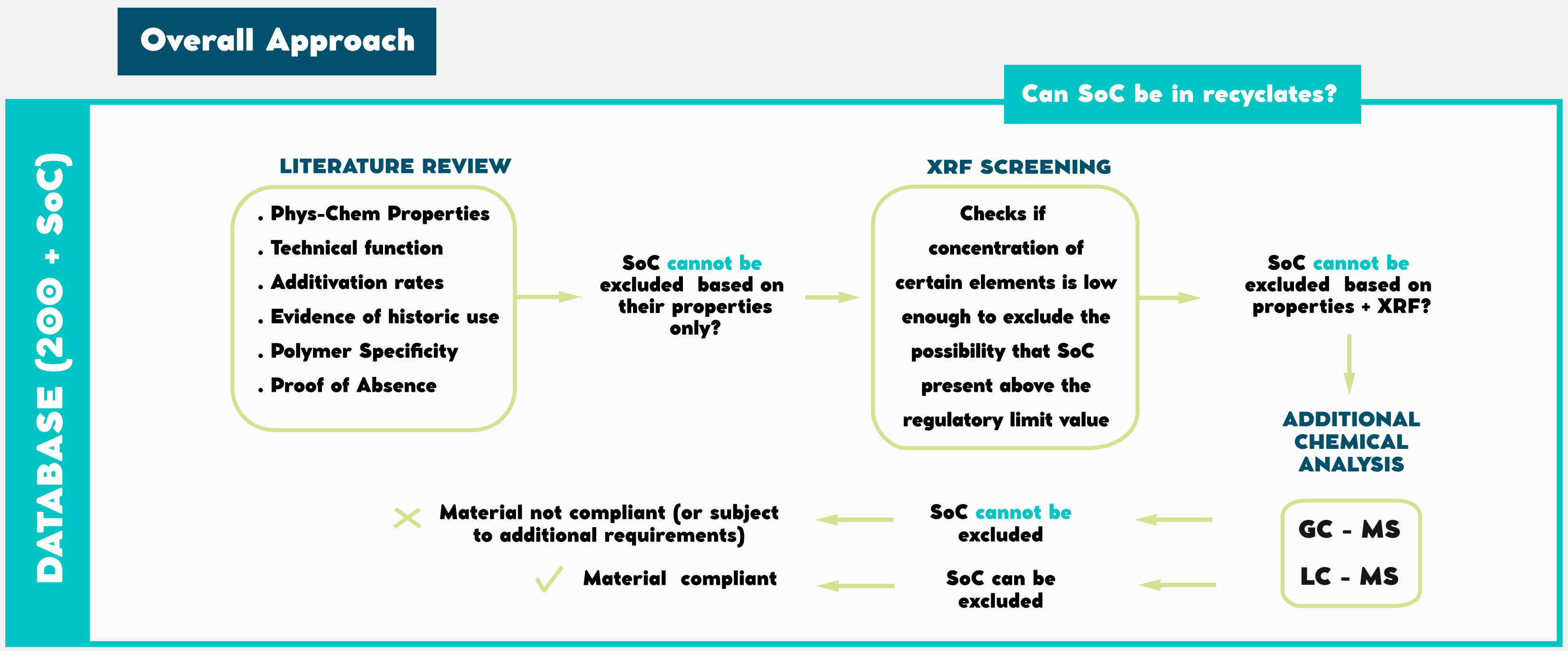

Figure 1. Overview of PRE-1000 industry standard and its key pillars.

- X-Ray Fluorescence (XRF) at the recycler's site to detect elements linked to regulated substances.
- Chemical Analysis (e.g., GC-MS/LC-MS[5]) for substances undetectable by XRF, providing precise measurements of volatile and non-volatile compounds.

3. BENEFITS AND IMPLEMENTATION OF PRE-1000

By using an Excel-based tool for quick SoC monitoring, recyclers can efficiently assess regulatory compliance, reducing the number of costly chemical testing. When properly implemented, PRE-1000 not only supports recyclers in fulfilling legislative demands but also contributes to public health and environmental protection by ensuring that recyclates do not pose adverse risks. This aligns with the WFD[5] "End-of-Waste" criteria, which mandates that recycled products must not harm human health or the environment.

4. KEY TAKEAWAYS

In summary, PRE-1000 simplifies compliance for recyclers by providing a manageable approach to monitoring hazardous substances in recycled plastics, balancing regulatory compliance with practical, economical screening solutions. A full guidance on the use of the PRE 1000 can be found in the public deliverable D1.2.

[5] Waste Framework Directive

All-round sustainability methodology

Julia Cilleruelo and Ashrakat Hamed, GreenDelta

Sustainability can be measured in different ways and can have many perspectives. A very commonly found metric nowadays, for example, is the carbon footprint of a product, service, or institution. We are used to hearing that the lower the carbon footprint the better. Clearly this is important as Climate Change is a global issue and is directly impacted by increased amounts of greenhouse gases in our atmosphere, but, what other perspectives can we take into account when assessing the sustainability of a product?

1. LIFE CYCLE ASSESSMENT (LCA)

On the one hand there is **Life Cycle Assessment** (LCA), which assesses environmental impacts at all life cycle stages: from the extraction of raw materials until end-of-life treatment processes. This practice is used, for example, to measure Climate Change impact (kg CO_2 eq.), but it can also yield results in other impact categories like Acidification Potential or Eutrophication of freshwater which disrupts ecosystems, Hu-

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man Toxicity which measures the impact on our health, or Water Use/Deprivation.

In PRIMUS, the **goal** of the LCA studies is to evaluate the environmental impact of the demonstrator cases performed within the project, both for internal project learnings as well as for public documentation, helping understand the benefits (and drawbacks) of using recycled content in high-added-value plastic products. There are 4 demonstrator cases being investigated as part of the **scope.** Their functional unit and system boundaries used for the assessment are shown in Figure. More information about each individual case is described in each of the dedicated demonstrator cases sections of this book.

In PRIMUS, byproducts from recycling processes are **allocated** by mass, where there is a cut-off after byproducts are made: no further treatment of the byproduct is taken into account but also no credits are given. Furthermore, no credits are given to the system for incineration with energy production. It is important to note that decisions over how to allocate byproducts of recycling processes have a lot of weight in final results and a sensitivity analysis is recommended.

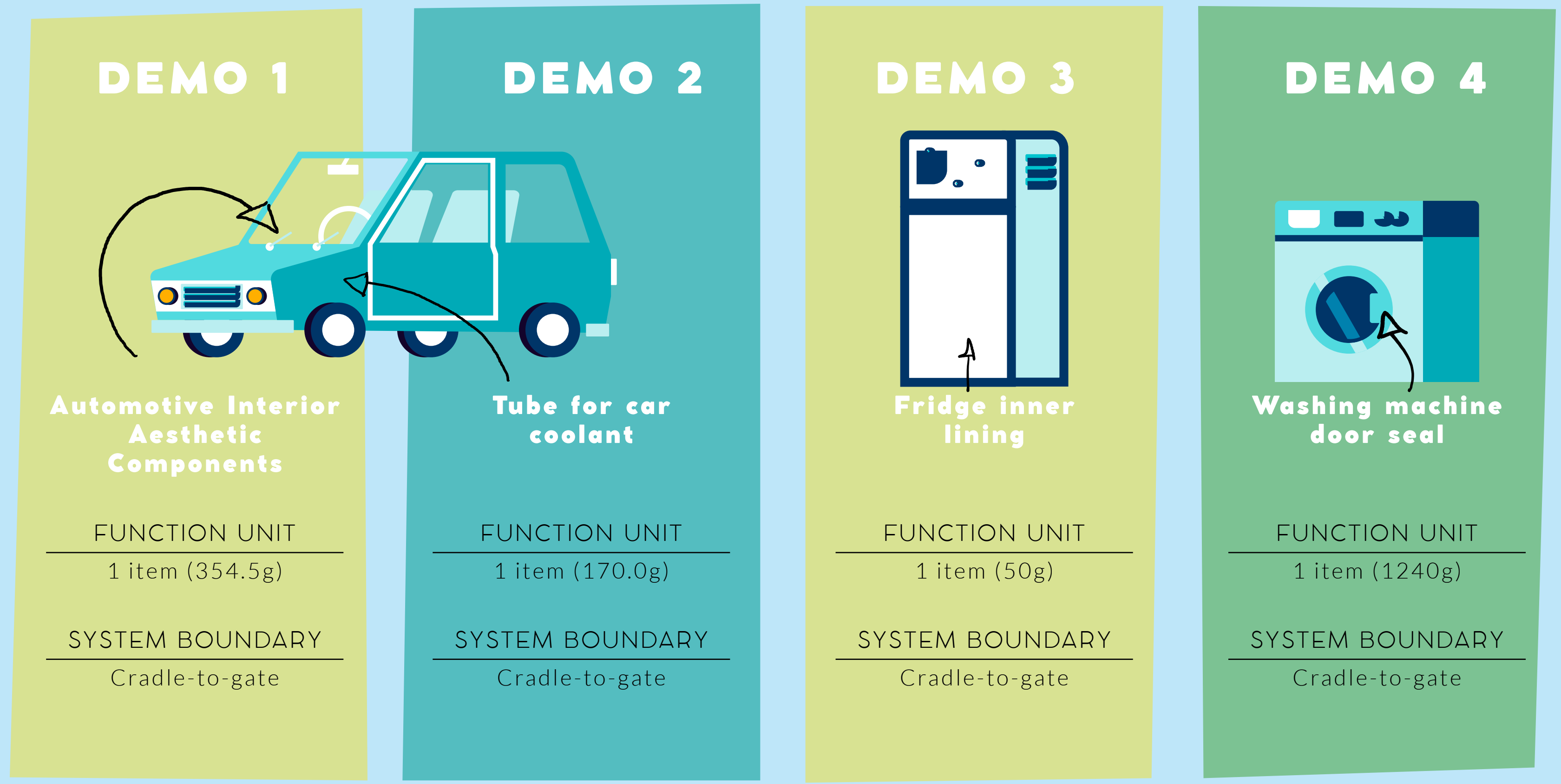

Figure 2. Functional units and system boundaries in PRIMUS demo cases.

Primary data was obtained from the different partners involved in the demonstrator cases, for raw material formulation and production processes. The ecoinvent 3.10 cut-off LCA database was used for background processes, and calculations were run with the Environmental Footprint 3.1 Life Cycle Impact Assessment Method provided by ecoinvent in their data package.

LCA is a very common practice to assess sustainability, but its perspective can be widened with other measurements.

2. SOCIAL LIFE CYCLE ASSESSMENT (SLCA)

The chemical and plastics industries have significant social impacts on workers, communities, and consumers. To assess these effects, a sLCA was conducted for the four PRIMUS demonstration cases, each using either primary or recycled plastics. 70 potential indicators from the PSILCA v3.1.1 database, covering four stakeholder groups, workers, local communities, value chain actors, and society, were considered.

The selection of indicators was carried out in three steps: (1) a social hotspot review using

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PSILCA data for European plastic production, (2) alignment with the EU Circular Economy Action Plan, and (3) expert judgment through a survey. Based on this process, 13 indicators were selected, with a primary focus on worker health and safety due to their relevance to the study's scope.

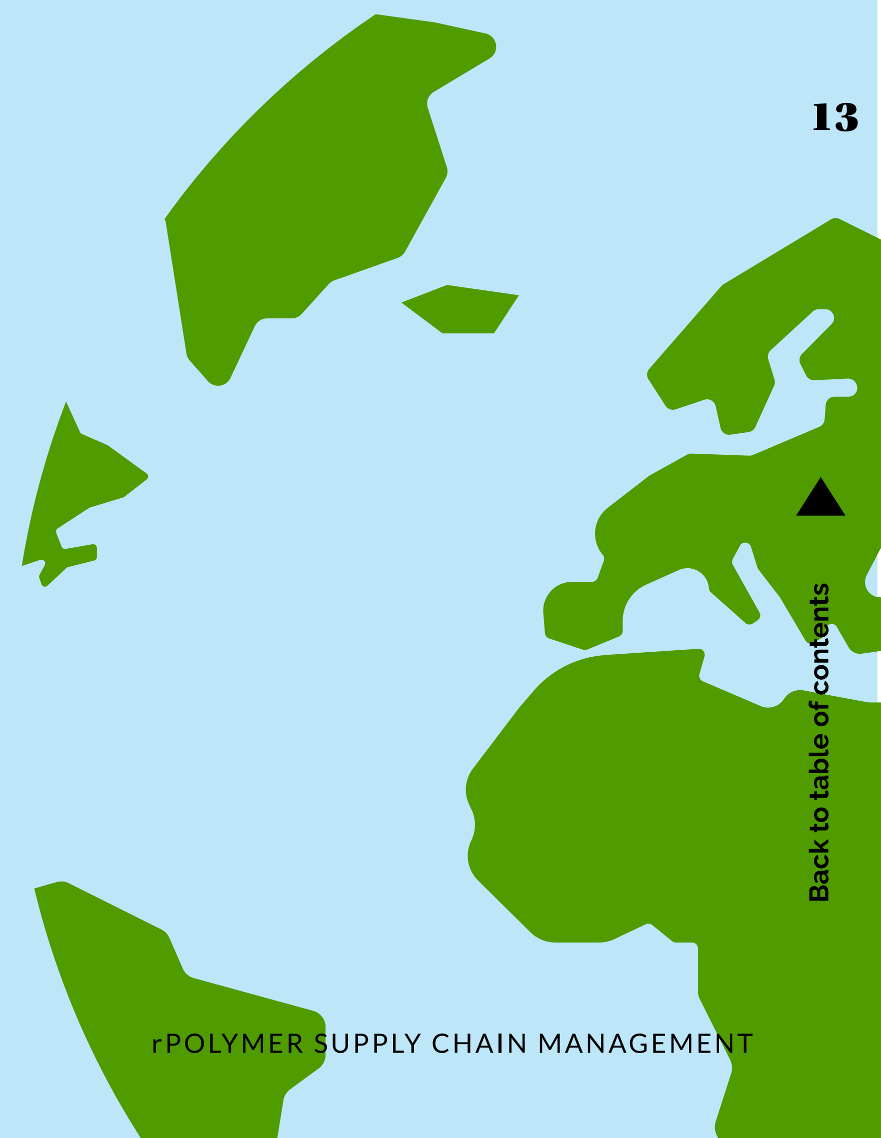
To improve future indicator selection, it is recommended that weighted input from industry experts is incorporated, and that the expert panel is expanded to include professionals directly involved in plastic production and recycling. Data collection primarily relied on the PSILCA database, with limited primary data obtained from Global Reporting Initiative (GRI) reports. More comprehensive monetary and social data from end-of-line supply chain companies would enhance the accuracy of social indicator assessments.

Preliminary calculations were performed using the SOCA v3.0 database, though PSILCA is recommended for country-specific supply chain data. Raw indicator values were analyzed instead of converting them to medium-risk hours, as such conversions may obscure whether a social indicator is improving or worsening. Interpreting raw data allows for clearer insights into social conditions and supports more informed decision-making

From an sLCA perspective, differences between primary and recycled scenarios do not drastically shift overall social metrics; however, monitoring labour conditions and safety compliance in recycled supply chains may require greater attention due to higher reported violations (e.g., labour violations in Demo 1 rose from approximately 7.5 to ~11.3 cases per 10,000 employees when switching from primary to recycled feedstocks). Meanwhile, national context remains a dominant factor in shaping social outcomes, as country-level differences, such as living wages (Finland's $1,000+ vs. Spain's $400 range), average weekly work hours (46 h vs. 30 h), and accident rates (496-511 vs. 56-96 per 100,000 employees), are far greater than the relatively modest variations observed between primary and recycled plastics.

3. PLASTIC LITTERING RISK

Plastic littering is also an evidently relevant metric when speaking about plastic products. For the PRIMUS project, plastic litter is measured using a probabilistic approach of the amount of plastic that is at risk of being littered per process of the LCA model. It is made by applying the PLEX database, a database developed by GreenDelta, into the already existing LCA models.



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4. CIRCULARITY ASSESSMENT

The benefits of including recycled content can also be measured with Circularity indicators. Those chosen as part of this methodology are the **Material Circularity Indicator** (MCI) by the Ellen MacArthur Foundation and the **Circularity Index** (CI) by Cullen (2017). These can expand the assessment for a comparison when varying the lifetime or number of uses of the product, or the energy used for secondary material production vs. primary material, or understanding how much primary material is needed or waste is produced in more and less circular scenarios. The indicators go from 0 for a linear product to 1 for a fully circular product.

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rPOLYMER SUPPLY CHAIN MANAGEMENT

All the above ways to measure sustainability have been adapted in this methodology to fit Life Cycle Assessment. That way, when making an LCA model one can also assess social LCA, plastic littering risk and Circularity. The work has all been clustered into a single, master, PRIMUS LCA database that can be accessed in openLCA Nexus.

5. SYSTEM DYNAMICS

In the context of the PRIMUS project, we use System Dynamics to model a transition from primary plastic production to a combination of primary and secondary plastic production, assessed over time. The focus of the model is to understand how stocks involved in the life cycle affect each other, how plastic littering evolves over time and unwanted substances in plastics for recycled products.

Specifically, the model is looking at a period of 1950-2060 to see, and quantify, the difference between a business-as-usual scenario where no recycled content is put to plastic parts, and a scenario with a goal of achieving 50% recycled plastic content in plastic parts by 2030, aiming for a circular economy.

The model is made generic to the world and all plastics and aims to validate its structure. The idea is to further iterate the generic model looking at specific types of plastics, use cases, or regional scenarios.
The main conclusions are:

1. A growing demand/production of plastics, and not enough recycling rates make a "circular economy" hard to reach. End-of-life recycling rates of products are too low to cover the supply of recycled material for new products.

2. LCA impact categories show improvements for the recycled product scenarios.

3. Overall environmental impacts become worse per year because of the increasing number of plastic products being demanded (or produced), independently if they have recycled content or not.

4. However, LCA impact categories do show an improvement for the recycled product scenarios.

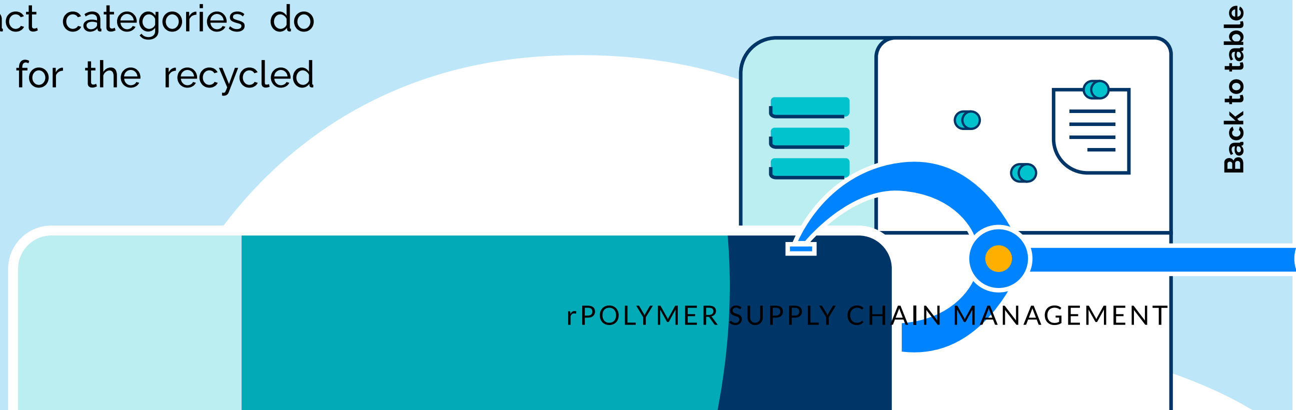
5. A 50% recycled content in products scenario helps dampen environmental impacts in LCA categories, making a real change. But this is not possible to achieve with current predicted recycling rates, or even eager prediction scenarios.

6. Littering is the most common EoL fate and is often overseen in assessments. It doesn't show a decrease in the recycling scenarios.

7. Increasing rate of plastics production comes with an increasing rate of littering.

8. The most effective way to reduce overall littering of plastics is EoL alternatives to landfill.

9. Unwanted substances in plastic products will be prolonged in the use phase if we recycle products.



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6. DATASETS FOR PRIMARY AND RECYCLED PLASTICS, AND ECOPROFILES

Environmental impacts of materials can have a big contribution to total LCA results. For that reason, having good and representative datasets for primary and recycled plastics is important.

Different datasets were available for **primary plastics.** A big dataset provider in Europe is Plastics Europe, with their EcoProfiles. Here, data is directly collected by plastic producers, and their reach is usually above 75% European market representation. The drawback from Plastics Europe's EcoProfiles is that some are relatively old and therefore end up with outdated electricity mix and process data. The ecoinvent, and Carbon Minds databases use these EcoProfiles as a basis for their primary plastics datasets. Other dataset providers for primary plastics are the LCA Commons, Environmental Footprint 3.1. From all of these, the ecoinvent database was chosen as it provides a good background database for the LCA model and uses the plastic data adapted mainly from the EcoProfiles from Plastics Europe.

In contrast to primary plastics, **secondary plastic datasets** were more difficult to track down. The quality, coverage and availability of Plastics Europe's EcoProfile datasets has not yet been achieved for secondary plastic EcoProfiles. At the time of writing this book, secondary plastics EcoProfiles had been published by Franklin Associates[6] for rHDPE, rPET, and rPP for the American market and by SRP Recyclage[7] for rPS, rPVC, rLDPE, rHDPE, rPET, and rPP for the French market.For the European market, the lack of transparency of the SRP Recyclage studies presents a challenge for LCA practitioners, as the provided EF 3.1 LCIA results require disaggregated, transparent data for use in modelling. At the time of making the case

[6] Franklin Associates. (2018). Life Cycle Impcats for Postconsumer Recycled Resins: PET, HDPE, and PP. The Association of Plastic Recyclers. https://plasticsrecycling.org/wp-content/uploads/2024/08/2018-APR-LCI-report.pdf

[7] SRP. (2023). Éco-profils des MPR. SRP Recyclage. https://www.srprecycle.com/eco-profils-des-mpr-2024

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Table 1. RPlastics: Availability of secondary plastics datasets from EcoProfiles and LCA background databases, compared to primary EcoProfiles from PlasticsEurope

	Primary EcoProfiles	Franklin Associates	SRP Recyclage	ei v3.10	ei v3.11	EF3.1	PRIMUS EcoProfiles
ABS	✓				✓		✓
PC	✓					✓	
PET	✓	✓	✓	✓	✓	✓	✓
PE	✓	✓	✓	✓	✓	✓	✓
PMMA	✓						
PP	✓	✓	✓		✓	✓	✓
PS	✓		✓		✓		✓
PU	✓						
PVC	✓		✓		✓		✓
PA	✓					✓	

studies, traditional databases contained few datasets for secondary plastic materials. The [ecoinvent v3.10 database](), for instance, contains only generic recycled plastic granulate datasets, recycled HDPE datasets and recycled PET datasets. As of the recent v3.11 update of the database, several new datasets for plastic recyclates add to the existing body of data. Furthermore, other databases, such as the Product Environmental Footprint project[8], provide numerous aggregated recyclate datasets but are restricted in their application to PEF and OEF studies[9] . An overview of the available datasets can be found in Table RPlastics. If accessible, the recent ecoinvent update v3.11 provides the most comprehensive and transparent set of recycled plastic data.

As part of the PRIMUS project, a public release of transparent and comprehensive EcoProfile datasets for plastic recyclates is planned for the spring of 2025 (see next section).

Table RPlastics: Availability of secondary plastics datasets from EcoProfiles and LCA background databases, compared to primary EcoProfiles from PlasticsEurope.

[8] European Commission. (2023, June). Nodes containing EF data. European Platform on LCA | EPLCA. https://eplca.jrc.ec.europa.eu/LCDN/contactListEF.html

[9] European Commission. Joint Research Centre. (2020). Guide for EF compliant data sets. Publications Office. https://data.europa.eu/doi/10.2760/537292

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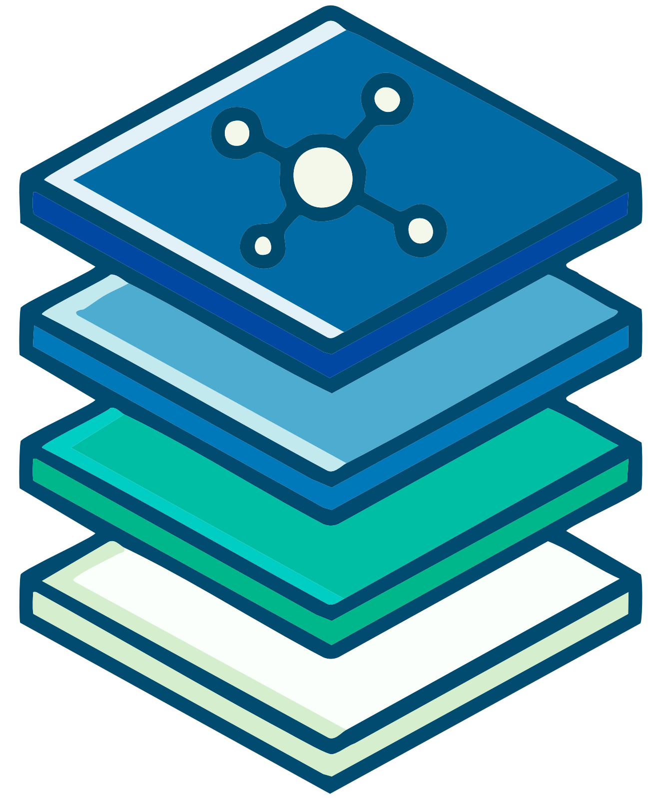
Ecoprofiles

Jonas Hoffmann, GreenDelta

EcoProfiles, firstly introduced by PlasticsEurope in 1993, are Life Cycle Inventories (LCIs) that provide cradle-to-gate data for European chemical production. These inventories cover raw material extraction, energy supply, and production processes, including emissions to air and water.

The EcoProfiles developed within the PRIMUS project provide **average European LCIs for mechanically recycled plastics** from various waste streams, focusing on WEEE plastics (rABS, rHIPS, rPVC, rPP). As opposed to the already existing EcoProfiles, they hold a transparent life cycle inventory.

Best practices were to perform a stakeholder mapping, which allowed to identify that LCI data is crucial for LCA practitioners, whilst LCIA results are valuable for the plastics industry and policymakers. Hence, EcoProfiles must include comprehensive descriptions of recycling processes and harmonize terms for consistency. Data collection relied on LCA practitioner templates for uniformity, but the collected data lacked information on microplastics, particulate matter, and VOC formation, which may lead to underestimated environmental impacts of recycling. Alternative methods, such as GreenDelta's plastic littering risk approach (PLEX database), and sensiticy analysis are recommended to fill data gaps like these. Selecting an appropriate LCA database was hindered by legal restrictions rather than data availability. For example, the Environmental Footprint 3.1 database was dismissed due to the requirements to use the Product Environmental Footprint standards. To ensure reliability and protect data, primary data was collected from at least three recycling sites per polymer type and region. When this was unfeasible, European average datasets were created using capacity-weigh-



ted averages, adaptable via regionalization for energy mix, waste treatment, and transport distances. Secondary data was used to fill the data gaps for waste collection.

Transparency was a critical aspect of developing EcoProfiles within the PRIMUS project. Each step in the data collection, processing, and reporting was clearly documented. Additionally, a Pedigree matrix data quality approach was used to assess the uncertainty of the data via Monte Carlo simulations. This is an improvement from already existing EcoProfiles and clearly documents the uncertainty of the calculation.

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Furthermore, cross-validation with existing datasets was performed to ensure consistency and accuracy across different data sources and methods. Providing disaggregated datasets and documenting each step of the methodology helped users comprehended the results and increases the likelihood of adoption. Finally, the work was internal and externally reviewed by uninvolved LCA experts with fruitful outcomes.

Eight key EcoProfiles were developed: rMPO, rLDPE, rHDPE, rPET, rABS, rPS, rPP and rPVC. A regionalization was performed only on the PRIMUS-related WEEE and high-value polymers (rPP, rHIPS, rABS). This led to the creation of >50 EcoProfiles. We could learn that, in all cases, recyclates perform better compared to primary materials for selected environmental impact categories. The results indicate reductions in Acidification, Greenhouse Gas Emissions and Fossil Resource Consumption across various polymer types. The assessments also reveals that environmental impacts strongly vary based on the polymer type and the origin of waste streams.

Type	Scope	EcoProfile description	Polymer datasets
Flakes	Gate-to-gate EU27+3	EU27+3 EcoProfile	rABS, rPET, rLDPE, rHDPE, rPP, rHIPS, rPVC
	Cradle-to-gate EU27+3	EU27+3 EcoProfile including collection and sorting	rABS, rPET, rLDPE, rHDPE, rPP, rHIPS, rPVC
	Gate-to-gate Regionalised	EcoProfile regionalised to AT, DE, FR, IT, NL, UK	rABS, rPP, rHIPS
	Cradle-to-gate Regionalised	EcoProfile including collection and sorting regionalised to AT, DE, FR, IT, NL, UK	rABS, rPP, rHIPS
Pellets	Gate-to-gate EU27+3	EU27+3 EcoProfile	rABS, rPET, rLDPE, rHDPE, rPP, rHIPS, rPVC
	Cradle-to-gate EU27+3	EU27+3 EcoProfile including collection and sorting	rABS, rPET, rLDPE, rHDPE, rPP, rHIPS, rPVC
	Gate-to-gate Regionalised	EcoProfile regionalised to AT, DE, FR, IT, NL, UK	rABS, rPP, rHIPS
	Cradle-to-gate Regionalised	EcoProfile including collection and sorting regionalised to AT, DE, FR, IT, NL, UK	rABS, rPP, rHIPS

Table 2. Summary of datasets published as part of the PRIMUS project.

The **outcome** of this work is:

- One PRIMUS EcoProfile Methodology for all polymers (https://cordis.europa.eu/project/id/101057067/results)
- 50 individual PRIMUS EcoProfile reports (https://www.plasticsrecyclers.eu/library/)
- 50 PRIMUS EcoProfiles datasets (aggregated and disaggregated datasets are available as ILCD and JSON-LD data formats) (https://nexus.openlca.org/databases)

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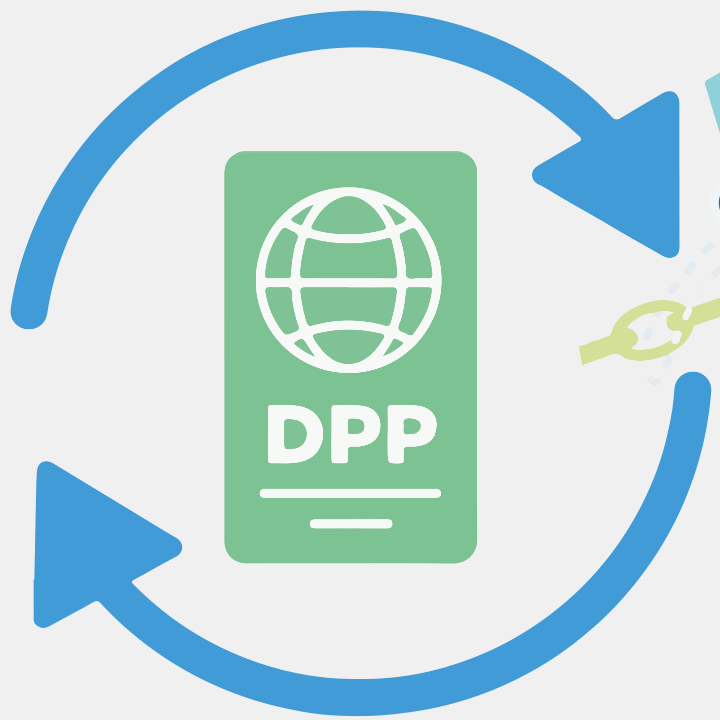

Traceability and digital product passport of recyclates

Daniel Gregory and Teresa Oberhauser, Circularise

"Recycled products must not harm human health or the environment."

Traceability of polymers is critical for improved recycling rates. Understanding the history of plastics helps to show what type they are and what impurities are present.
This allows:

- Recyclers to more easily sort and customize the cleaning process, removing impurities and previous additives such as brominated compounds,

- Compounders to tailor additives to the recyclate based on the prior use of the recyclate (therefore likely current impurities not removed by above point) and future use.

- Part manufacturers to increase trust in recycled materials for high performance applications, increasing the pool of available uses for recycled plastics.

Within a traceability system, there is data describing the material being traced. This includes measurable quantities like the physical properties of the material, the ideal pro-

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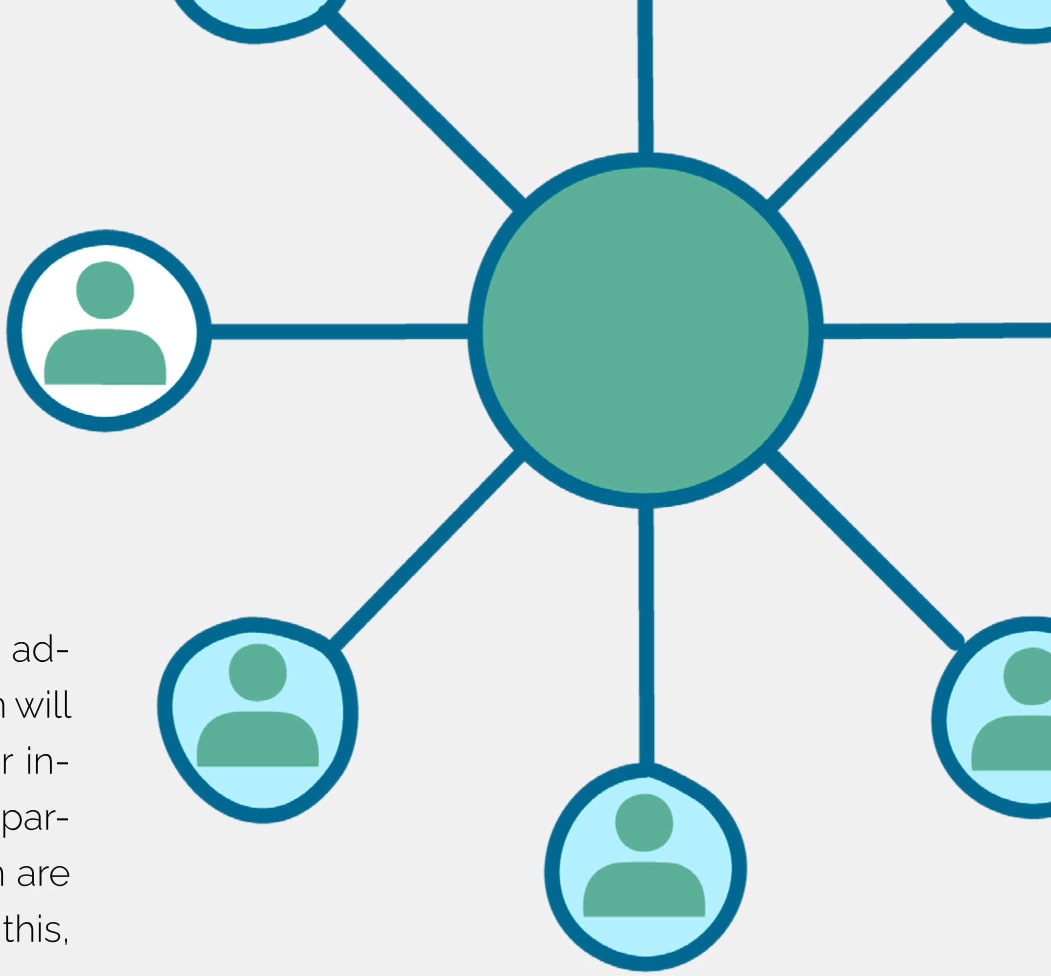

cessing conditions or handling conditions, and the chemical composition. It can also include assigned properties such as regulatory certification, assembly or disassembly documents for efficient recycling, or safe handling protocols. The system also contains information on the provenance of a material and its chain of custody. This is a record of who had the material at what time and where. Finally, authenticity and verification of the data and provenance is also traced.

1. GETTING THE DATA

Data can be gathered by many different processes, but it is best to have different tiers of the supply chain work together. In this best practice, a working group representing all stakeholders in the industry should gather for a series of discussions. These discussions should be moderated by a disinterested third party, for example the data carrier. Organizing the working group may prove challenging, for example stakeholders adjacent to each other on the supply chain will be reluctant to divulge trade secrets or information. This can happen when two parties of the same tier in the supply chain are present in the working group. To avoid this, it is recommended to use some legal system that prevents stakeholders from using the information in the system, for example a non-disclosure clause in an EU funding scheme or Chatham-house rules. At a government or intergovernmental level, having 2 or more working groups can be considered, with separate entities within them. This also allows to compare results and data points.

When conducting the interviews, one can begin with the highest tier of stakeholder in the supply chain. This stakeholder should talk through three key aspects of their operations:

- **What information do they need** or will they need about their inputs? If they use primary sources, what information do they get from the primary resource that affects its quality? If they use secondary resources, what information do they have on its previous history?

- **What information do they need to provide their customers**, and is there information their customers want that they do not provide for security reasons?

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- **What kind of data do they need to provide for regulatory purposes?** This can be demonstration of compliance with legislation, a voluntary standard, or it can be the data required to produce an LCA report.

It is important to regularly check in with the stakeholder to ensure their comfort in sharing this information. If required, a confidential communication channel can be opened to share information with the governing body setting up the traceability system. However, it is important to share the data categories listed with the other stakeholders, which is why this is best done in a group. As two of the above points involve other stakeholders in the supply chain (either suppliers or customers), room should be given for the rest of the working group to comment on these data points. Is there anything missing that other stakeholders would find useful?

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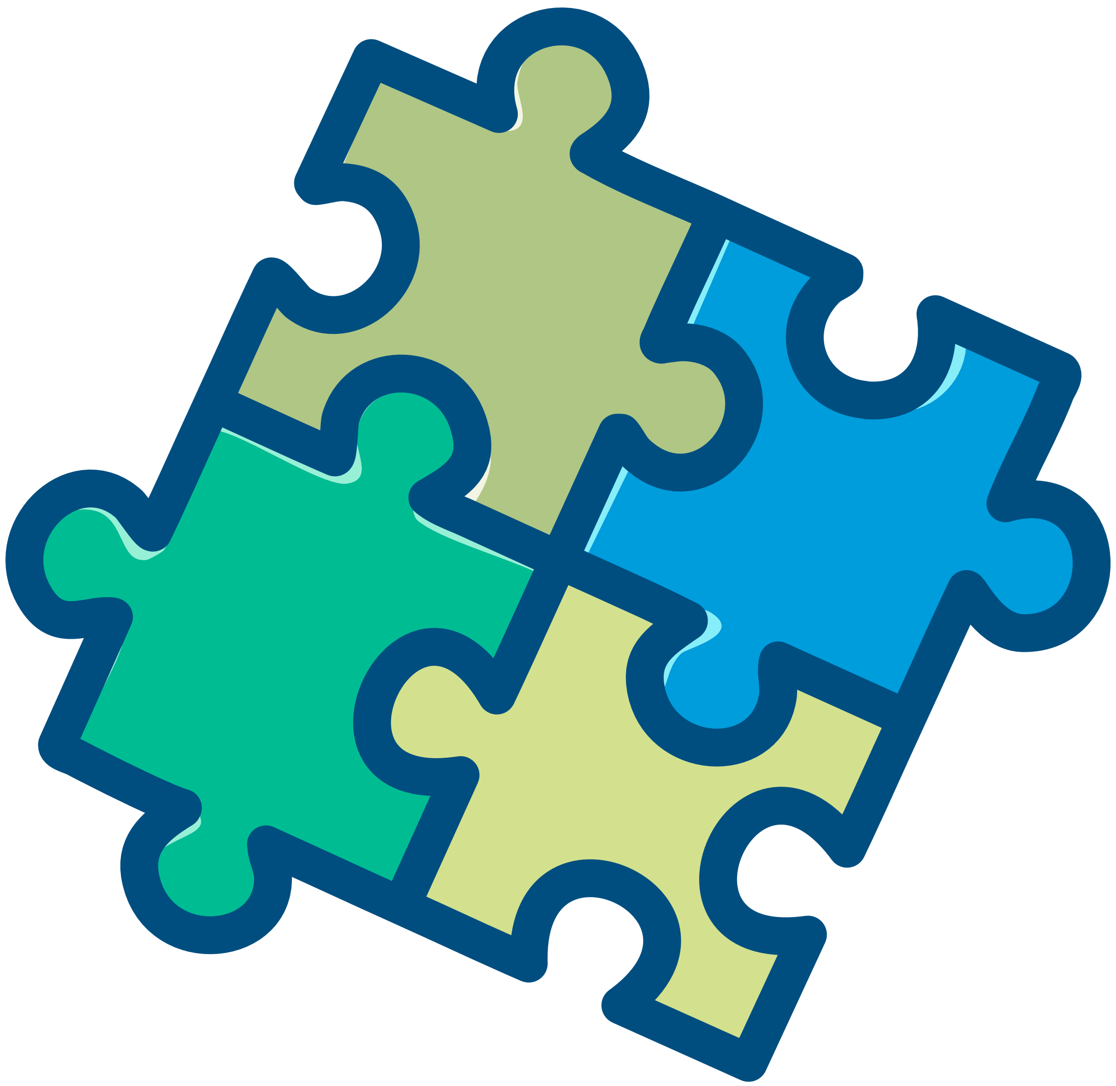
Quality-Quantity-Match Model

Pekka Laurikainen and Farzin Javanshour, VTT



The PRIMUS quality-quantity match model sets an example framework for demand driven circular economy in WEEE and end-of-life vehicle plastics. The aim of the framework is to provide stakeholders with a systematic mapping tool to pinpoint application-specific technical and regulatory requirements for sourcing recyclates with consistent quality, at economies of scale.

By using the proposed framework, stakeholders would be able to identify the most impactful enablers and barriers i.e., 'low-hanging fruits' for recyclate uptake. The identification of low-hanging fruits is done based on a fuzzy model providing numerical quality level to each operation and its output depending on the target application of recyclates. A graphical representation of the PRIMUS quality-quantity match model is presented in Figure 3. The fuzzy match model results define the viability of specific waste stream and recycling operation (on scale of 1: not viable- to 5: ready for implementation) based on the **technical quality index** (case specific weights) and the **value-chain quality index** (on scale 1: emerging, actor being sought out- to 3: well established).

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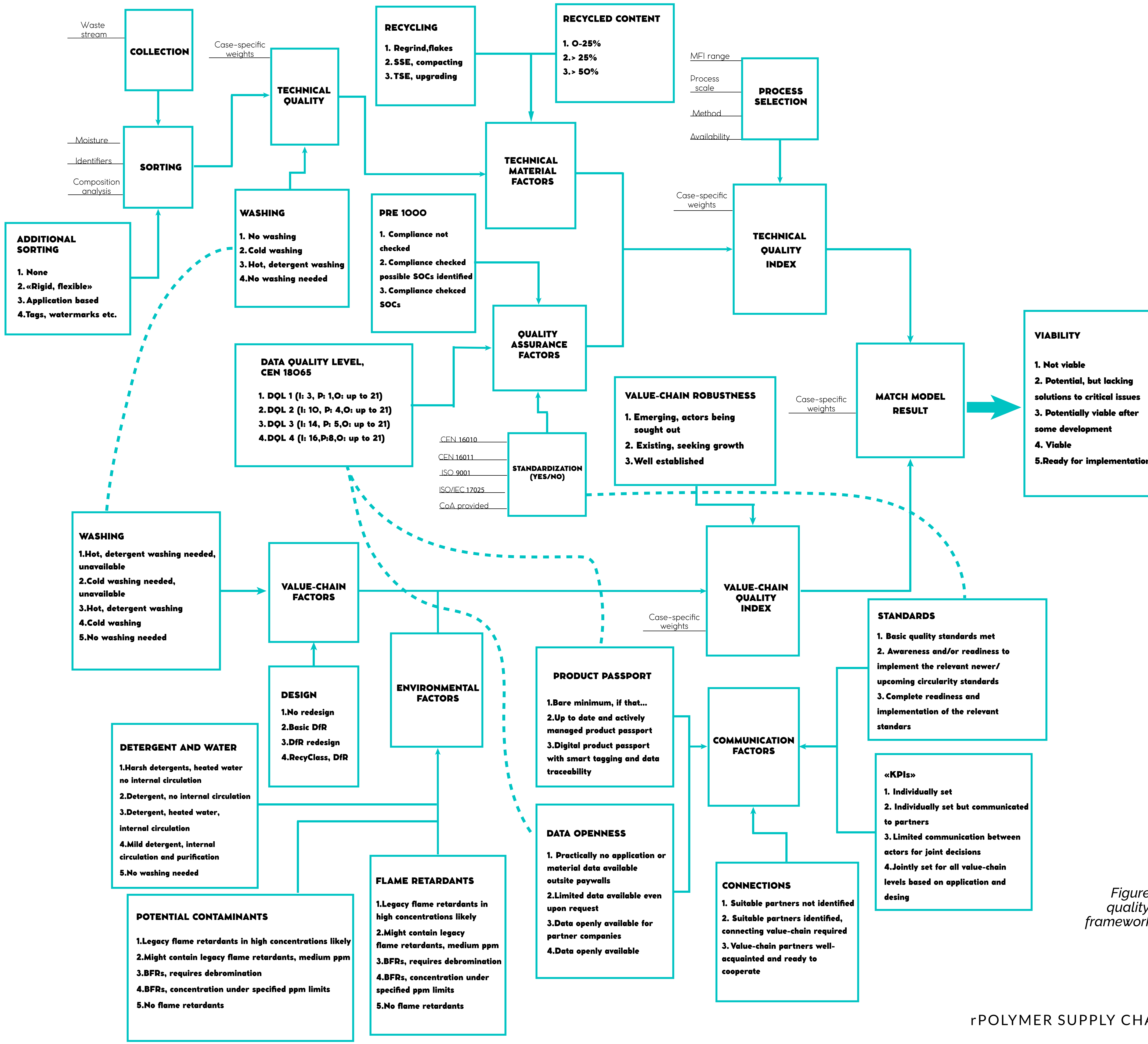

Figure 3. Overview of PRIMUS quality-quantity match model framework based on fuzzy model approach

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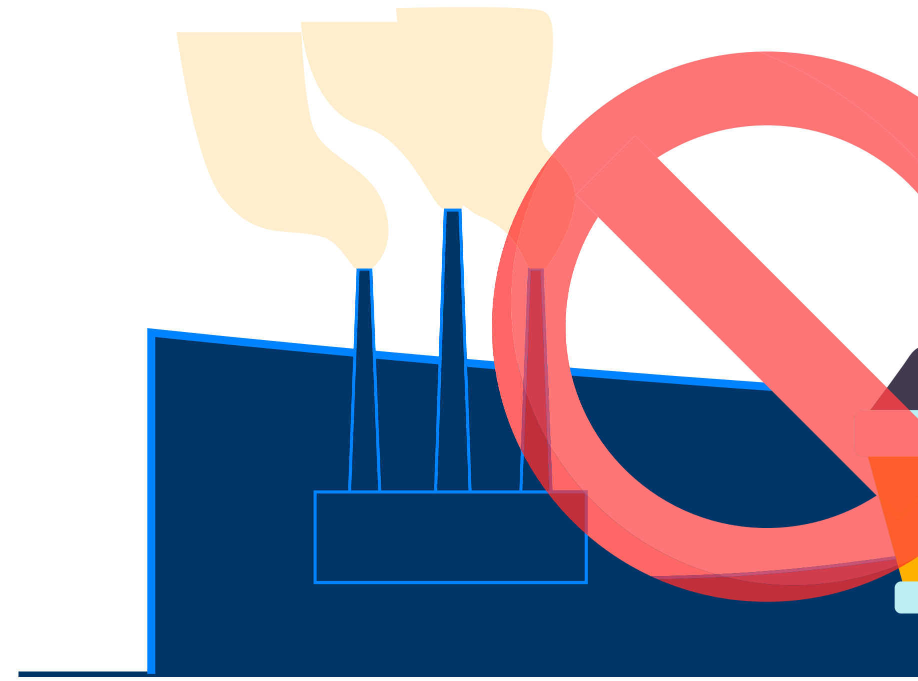
rPOLYMER SUPPLY CHAIN MANAGEMENT



The **technical quality index** (upper half of diagram in Figure 3) is defined by case-specific weights as a function of (i) technical material factors and (ii) quality assurance factors. The technical material factors are a function of:

- Technical quality of sorted waste stream: including sorting quality (on the scale of 1: only composition based, 2: additional rigid/flexible sorting, 3: application specific sorting, 4: supplementary sorting), and washing quality (on the scale of 1: contaminated and not washed- to 4: clean, no need for washing).

- Form and composition of recyclates: including recyclate content (on the scale of 1- to 3), and recycling form (on the scale of 1: flake, regrind, 2: single screw compacting and extrusion, 3: twin screw extrusion compounding and upgrading).

The quality assurance factors affecting the technical quality index are function of:

- PRE 1000 industry standard (on the scale of 1: not checked for PRE 1000, 2: checked for PRE 1000 and possible SoC identified, 3: PRE 1000 checked and no SoC).

- Classification of recyclates based on data depth and quality levels (DQLs) in compliance with prEN ISO 18065[10] (on the scale of 1- to 4). The DQLs ensure consistent recyclate labeling based on mandatory material information (I: e.g., main plastic, recyclate content, recycling method), material property (P: e.g., viscosity, density, ash content, material composition and tensile properties), and optional properties (O: e.g., chemical resistance, shear curve, and information on melt filtration, washing protocol, additives, and application).

- General information on applied material testing standards, and facility certification.

The **value-chain quality index** (lower half of diagram in Figure 3) defines the robustness of case-specific value chain (on scale 1: emerging, actor being sought out- to 3: well established). This index is a function of (i) communication factors (e.g., standards and regulations, identification stakeholders and partners, KPIs, data openness on level of operations and other types of data, and digital product passport), (ii) environmental factors (e.g., information on flame retardants, SIN listed materials and potential contaminants, detergents, water and energy consumption), and (iii) value-chain factors (e.g., compliance with design for recyclability, design from recycling, and RecyClass).

[10] prEN ISO 18065, Plastics – Recycled plastics – Classification of recycled plastics based on Data Quality Levels for use and (digital) trading.

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PROCESS INNOVA- TION

"Advanced" mechanical recycling

Jani Pelto, VTT

Mechanical recycling of plastics should always **target to achieve consistent and high quality** (see section 3.5 for the concise definitions for quality). For plastics with recycled content this is more difficult to achieve than with primary resin as there is an inevitable variation in the quality of recyclates between production batches over time, or even within a single batch. This poses a challenge to the designer and material processors – how can one reach high recycled content, say, between 50-70%, and consistently high quality? In most technical cases, the quality of the recycled stream is not sufficient without significant upgrading. Hence, very often, additives such as chain extenders, compatibilizers, impact modifiers, slip agents or lubricants, surface modifiers, colour pigments, stabilizers, etc. will be added to the final formulation.

The upgraded plastic or elastomer formulation, are typically made in single screw extruders, or nowadays more often in **twin screw compounding machines** that offer improvements such as efficient mixing of the melt and great flexibility in arranging the raw material feeders (each additive needs an individual gravimetric feeder), venting, and vacuum gassing port along the twin screw extruder.

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PROCESS INNOVATION

Extruders can be also arranged into a **cascade**, either single screw or twin-screw machine feeding the compounding extruder. Typically, in such cascade setup the purpose of the first extruder is to “eat” the bulky, fluffy, or inhomogeneous recycled material with some residual moisture content, e.g. film scraps or flakes into the process, making a homogenize melt. This generates enough melt pressure for the subsequent melt filtration and transportation downstream into the second compounding extruder where the additives and primary polymers are then introduced.

The term **“Advanced mechanical recycling” means Inline control of the composition of plastic formulation on the compounding line**, where the additives and primary resins are blended or compounded with the recyclate. Sensors are being applied in all within and between unit operations along the process, thus enabling the process control system to act proactively on the fluctuation in the recycled material stream and simultaneously act on any changes in output stream properties. The controlled properties of the melt are continuously measured using Inline rheometers, optical sensors, VOC sensors, and the gravimetric feeders for each of the components (polymers, additives) and continuously adjusted accordingly to respond to measured changes in the viscosity parameters, process conditions (use of energy, thermal history) degradation of the polymers in the melt, melt homogeneity, colour, etc – therefore enabling reproducible and constant quality within production single batch, or between batches, and also recording the properties of the compounds. The abundant information collected from the compounding line can be further processed and utilized in the Digital Product Passport, for example.

Fully operational Advanced mechanical recycling systems have been thus far **demonstrated in laboratory scale**. One example is the cascaded line (single screw to 27mm twin screw, up to 50 kg/h throughputs) cascade which is continuously being developed at VTT in Finland. This line has been successfully used in multiple demonstrator cases. For the PRIMUS project, it has generated rPC/ABS blends for 2K injection moulding of an automotive interior (aesthetic) component (Demo 1), and food grade rHIPS blends for refrigerator inner liner made by extrusion-thermoforming process (Demo 3). In both cases, high recycled content has been demonstrated. After the advanced mechanical recycling process, the rPC/ABS and rHIPS containing post-consumer recycled content shows mechanical properties and processibility comparable to the specific primary resins originally chosen to produce the plastic part.

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Inline VOC analysis

Jarkko J. Saarinen, University of Eastern Finland

Volatile organic compounds (VOCs) are a large group of organic chemicals that can easily evaporate at room temperature into vapors or gases. VOCs can be emitted by various products and materials, and they can have significant health and environmental impacts.

Emissions of **VOCs in plastic production are a significant concern.** The plastics manufacturing process involves the use of various chemicals such as solvents, monomers, and additives, which can be released as VOCs into the surrounding air. These VOC emissions can occur at different stages of the production from raw material handling to the actual production and finishing processes. This highlights the importance of monitoring these VOC emissions especially during the production and processing of plastics that involves elevated temperatures contributing to increased VOC emissions and thus, a potential hazardous risk for employees.

The most common VOCs released during plastic production include styrene, toluene, aldehydes, hydrogen chloride, and hydrogen bromide originating from the use of brominated flame retardants (BFRs).

During the PRIMUS project, a **protocol for detecting brominated gaseous compounds from melt plastics** was established. The analytical work started with well-known and validated tools using sorbent tubes that were analysed using both gas-chromatography mass spectrometry (GC-MS) and trapped ion mass-spectrometry in time-of-flight (TIMS-TOF) mode together with direct insertion probe (DIP).

Ex-situ VOC analysis for four PRIMUS demonstrator cases was evaluated. Three demonstrator cases were evaluated using both XAD and Tenax sorbent tubes together with a single-screw extrusion, whereas the VOC emission of the TPV/TPE constituent material was characterized using a TIMS-TOF mass spectrometry analysis together with DIP.

The ex-situ analytics was expanded to in-situ analytics in a twin-screw extruder by using inline Fourier-transform infrared spectroscopy (FTIR) analytics that were complemented with samples collected in sorbent tubes for validation and pair-wise correlation between the in-situ and ex-situ analytics. The inline sampling was collected using an in-house built sampling system attached to the vacuum degassing line of the compounding unit.

As a summary, the results obtained within the PRIMUS project indicate that it is vital to measure and control the VOC emissions during processing of plastics, especially when dealing with recycled streams. The developed ex-situ and in-situ analytics revealed the main emitted components that will be utilized as a starting point for a more detailed in-situ VOC analytics on the plastic up-conversion line. Finally, it was demonstrated that brominated gaseous compounds can be detected, identified, and even quantified using the inline, in-situ FTIR based gas analyzer.

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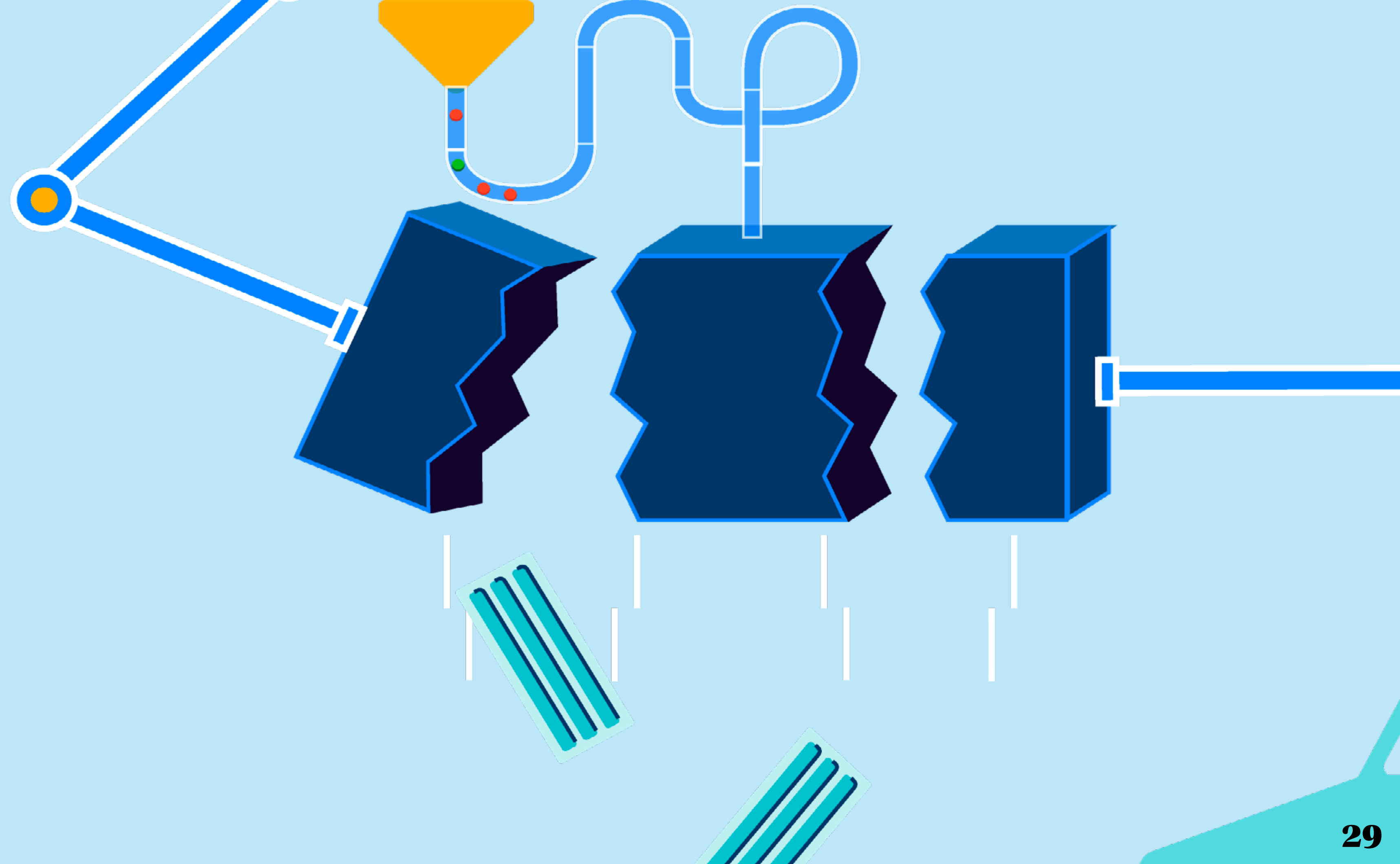

Degradation management

Jarkko J. Saarinen, University of Eastern Finland

Sensing technologies for identification and sorting of waste plastics are widely used in recycling plants, as several commercial solutions have become available during the past years. Most sensors in use consist of single point near- and mid-infrared (NIR and MIR) spectrometers. Quality control of recycled plastics is essential to ensure the desired properties for highly valued applications, allowing for a true circular economy. A NIR hyperspectral imaging was used in the PRIMUS Project to develop quantitative models as well as applying the same models to map the degradation degree on thermally aged plastic samples.

Within the PRIMUS project it was demonstrated the use of SWIR hyperspectral imaging to quantitatively predict the thermal degradation time of ABS and HIPS, two of the most relevant polymers in WEEE plastics. SWIR hyperspectral imaging was used to map, for the first time, the degradation degree in the samples and interpreted its limitations. The heatmaps of degradation time showed the importance of using hyperspectral images as opposed to single-point NIR spectroscopy. The broad heterogeneity observed even in degraded primary plastics could lead to large errors if a single point NIR spectroscopy was used to assess the material. Currently, the analysis is extended for the UV-degraded samples.

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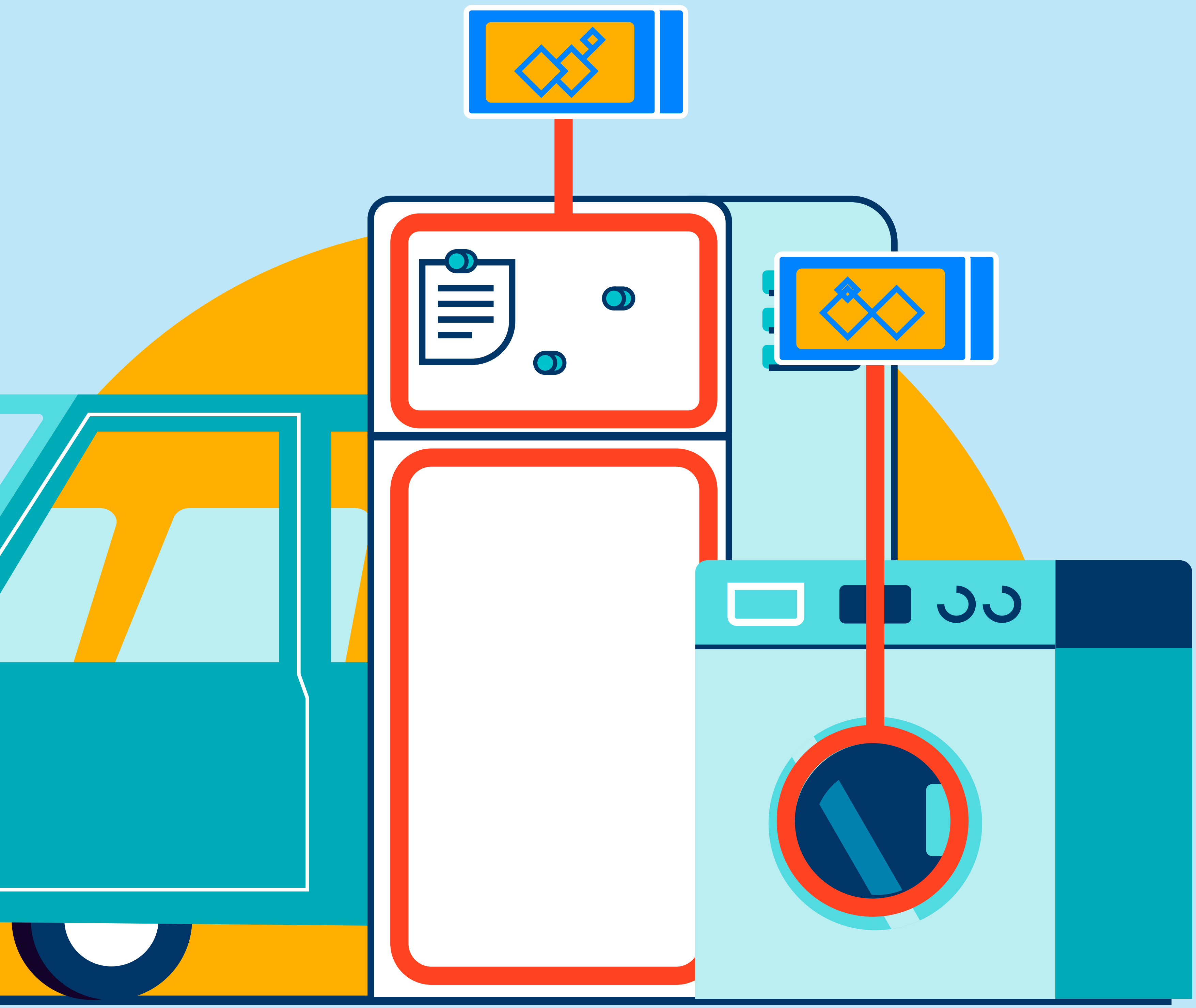

Debromination

Jarkko J. Saarinen, University of Eastern Finland

A significant portion of plastic waste remains unutilized, including many engineering plastics, such as polystyrene (PS), acrylonitrile butadiene styrene (ABS), and polycarbonate (PC). A major obstacle to their recycling is the presence of halogenated flame retardants, which are known to be harmful to both the environment and human health. Brominated flame retardants (BFRs) have been widely employed in plastics industry due to low decomposing temperature and high trapping efficiency. Over 75 BFR varieties have been commercially used, with tetrabromobisphenol A (TBBPA) being the most common. Developing an efficient process to remove BFRs is essential to facilitate the recycling of a broader range of plastic waste. In this section, elimination of BFRs is overviewed in the context of mechanical plastic recycling.

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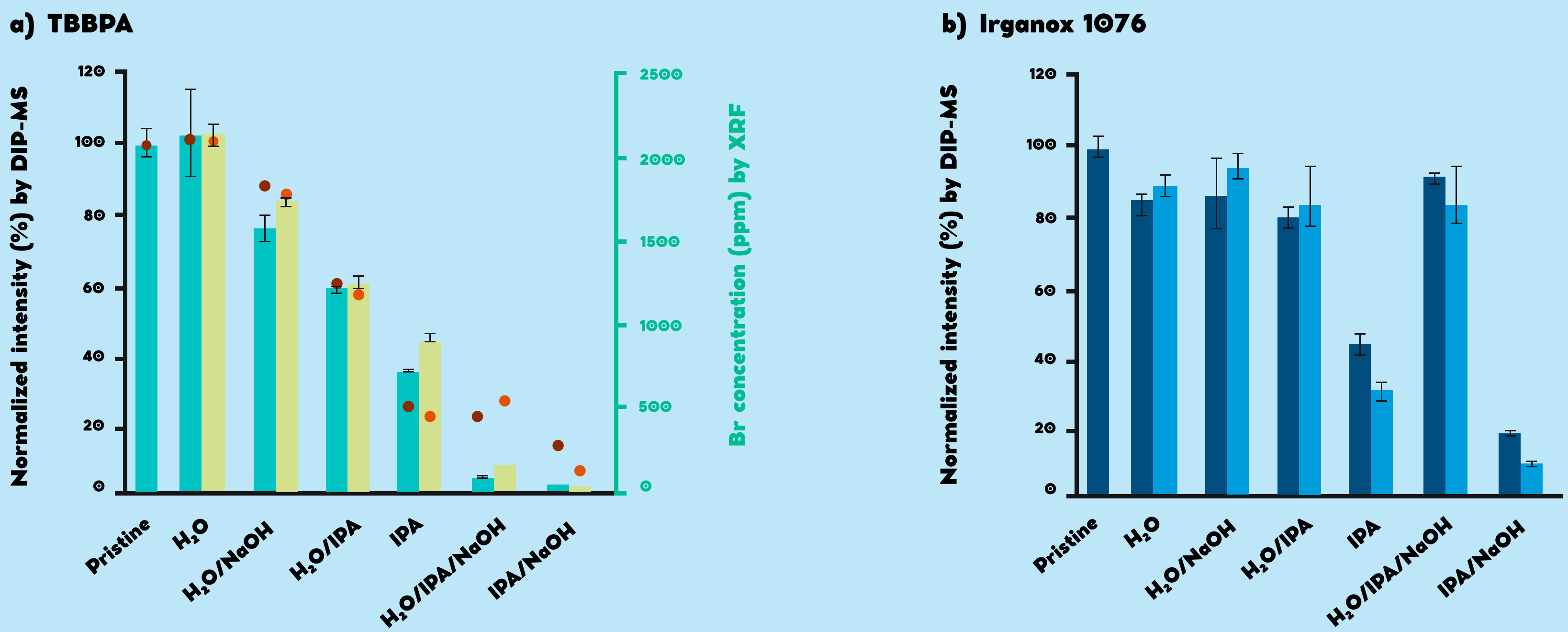

Figure 4. The effect of solvent composition on the total Br concentration based on XRF (dots on right axis) as well as TBBPA and Irganox 1076 antioxidant content based on DIP-MS (columns on left axis) of the HIPS sample in an extraction experiment at 100 ˚C for 1 h. Two extraction experiments were conducted with each solvent medium, illustrated as dark and light-colored columns and dots. Error bars represent one standard deviation between three parallel DIP-MS measurements.

Various successful strategies have been employed to eliminate bromine from plastics to enable recycling. Extractions target to **selectively remove BFRs from the plastic without degrading the polymer structure**. Extractions are typically conducted at elevated temperatures under ambient pressure, or as a solvothermal process in autoclaves. The extraction efficiency is highly dependent on the solvent-polymer-BFR combination.

In the PRIMUS project, a model mixture of high-impact polystyrene (HIPS) containing TBBPA and Sb 2 O 3 synergist, with bromine concentrations of 2500 ppm and 25 000 ppm, was prepared to study extraction methods. The BFR extraction was studied in solvent compositions consisting of mixtures of water, IPA, and NaOH, instead of relying on aromatic organic solvents such as toluene or xylene. Results of different solvent compositions are summarized in Figure 4.

Experiments were performed in a sealed autoclave under elevated pressures and inert atmosphere. Intriguingly, using 1:1 (vol:vol) H2O-IPA solvent with NaOH facilitated selective TBBPA extraction, without extensive loss of other additives, such as antioxidants, from the substrate. Extraction in this solvent composition proved to be most efficient at 125 ˚C, as higher temperature of 150 ˚C suppressed the extraction efficiency owing to the melting of the plastic. Extraction of TBBPA from HIPS was efficient with both 2500 and 25000 ppm model compounds using H2O/IPA/NaOH. Moreover, based on differential scanning calorimetry, 1H NMR, and size exclusion chromatography analyses, no significant polymer degradation was observed due to any of the applied extraction conditions. The main challenge was the observation that the extraction efficiency was highly dependent on the particle size, and cryo-grinding was necessary to achieve high BFR removal[11].

[11] P. Auvinen, V. H. Nissinen, E. Karjalainen, K. Korpijärvi, E. Olkkonen, K. Grönlund, I. Rytöluoto, L. Kuutti, M. Suvanto, J. Jänis, and J. J. Saarinen, Selective solvothermal extrac- tion of tetrabromobisphenol A to promote plastic recy- cling, Chemical Engineering Journal Advances 21, 100688 (2025).

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Mass-spectrometry analysis

Jarkko J. Saarinen, University of Eastern Finland

This section focuses on the mass spectrometric analysis of organic plastic additives, especially brominated flame retardants (BFRs), from plastic samples.

1. BACKGROUND

A common challenge in the characterization of plastics is the complexity of the samples, which can be composed of multiple polymers and a wide variety of different additives (fillers, antioxidants, plasticizers, flame retardants, colorants, etc.). The characterization of recycled plastics can be even more challenging due to the heterogeneity of waste streams and possible non--intentionally added substances (NIAS). In addition, many commercial BFRs are mixtures of different isomers or congeners, which further complicates the analysis.

Traditionally, the BFR analysis was performed using indirect analysis methods, which are based on solvent extraction or dissolution of the sample followed by chemical analysis using typically gas chromatography or liquid chromatography coupled with mass spectrometry (GC-MS or LC-MS). These chromatographic techniques are well established and enable accurate quantification of different compounds present even in trace amounts. However, the solvent extraction cannot always remove additives quantitatively from the polymer matrix, for example, due to poor solubility of certain analytes in suitable solvents. Furthermore, these techniques are cumbersome, time-consuming, expensive, consume substantial amounts of solvents and may also suffer from matrix effects. Due to these disadvantages, one goal of the PRIMUS project has been the development of analytical methods enabling analysis of additives directly from the plastic samples without extensive sample preparation. This kind of technical development is essential for a more effective recycling of plastics and safer use of the recyclates.

The most common method for directly indicating the presence of BFRs in plastic samples is XRF, which is a simple high-throughput analysis method requiring no complex sample preparation. However, XRF lacks the capability to discriminate between different brominated compounds as it measures the total elemental bromine content of the sample. Spectroscopic techniques, including IR and Raman, can be used to directly analyse flame retardants and other additives from plastic samples with minimal sample preparation. However, they are not sensitive enough to verify compliance with the low threshold levels set by the legislation. Hence, PRIMUS project decided to fo-

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cus on the development of sensitive direct mass spectrometric techniques for the characterization of plastic samples.

Direct mass spectrometric techniques enable the analysis of solid and liquid samples with minimal sample preparation and in a chromatography-free manner. Perhaps two of the most common direct mass spectrometric techniques for the analysis of solid samples, namely direct insertion probe (DIP) and atmospheric pressure solids analysis probe (ASAP), share a common operating principle: the sample is loaded into a capillary or a cup, which is introduced into the ion source equipped with a heater to vaporize or thermally decompose the sample. Volatiles are ionized often using ambient pressure ionization techniques, such as atmospheric pressure chemical ionization (APCI), and guided directly into a mass spectrometer. Other related analytical techniques include, for example, desorption electrospray ionization (DESI) and direct analysis in real time (DART).

2. WORK AND RESULTS FOR THE PRIMUS PROJECT

During the PRIMUS project, DIP-MS was found to be a viable tool for rapidly screening plastic additives from different classes, including antioxidants, plasticizers, light stabilizers, as well as halogenated and phosphorous flame retardants. The most notable advantage of DIP-MS is the minimal sample preparation required. Additionally, the DIP-MS measurements can provide valuable information about the composition of polymer matrices, including identification of the comonomers present. Figure 5 presents exemplary temperature-programmed DIP-MS data from a measurement of a high impact polystyrene (HIPS) sample containing TBBPA flame retardant and having a total bromine concentration of 2500 ppm (w/w). The measurement was conducted in a positive-ion mode using a high-resolution Bruker timsTOF PRO quadrupole time-of-flight (Q-TOF) mass spectrometer equipped with an APCI ion source. The top panel shows a total ion chromatogram (TIC) and the vaporizer temperature program ramping from 150 to 450 °C with 50 °C steps within 10.5 minutes. The bottom panels present averaged mass spectra obtained at 350 °C (left) and at 450 °C (right). TBBPA is readily identified from the mass spectrum recorded at 350 °C based on the accurate mass of the molecular ion and its isotope pattern. In addition to TBBPA, the sample was found to contain Irganox 1076 antioxidant and Cyasorb UV-2908 light stabilizer, both common polymer additives. At higher temperatures (450 °C), thermally generated polymer fragments (styrene oligomers) dominate the mass spectrum. The results presented herein provide an illustrative example of how DIP-MS measurements enable simultaneous qualitative analysis of additives and the polymer matrix[12].

[12] K. Grönlund, V. H. Nissinen, I. Rytöluoto, M. Mosallaei, J. Mikkonen, K. Korpijärvi, P. Auvinen, M. Suvanto, J. J. Saa- rinen, and J. Jänis, Direct mass spectrometric analysis of brominated flame retardants in synthetic polymers, ACS Omega 9, 33011-33021 (2024).

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The most notable disadvantage of DIP-MS is uncertainty related to acquiring quantitative data. This issue was addressed in the PRIMUS project by analysing micro compounded model samples consisting of either HIPS or ABS matrix and a BFR (decaBDE, TBBPA, HBCD). Although DIP- MS analysis with a small sample (<0.1 mg) cut from the plastic samples was found to be well suited for the direct qualitative analysis of BFRs from polymer matrices, repeatability of the measurement was found to be poor. By optimizing the sampling procedure through cryogenic grinding of the polymers and by increasing the sample size to approximately 1 mg, the repeatability of the measurements was significantly enhanced. As an example, a linear correlation between the DIP-MS intensity of decaBDE molecular ion signal and the elemental Br concentration of HIPS-decaBDE and ABS-decaBDE samples (XRF) was established in a concentration range from 0 to approximately 9 wt% with R2 values being 0.9988–0.9993 (Figure 5). Overall, the results show that DIP-MS holds the potential also for the quantitative analysis of all studied BFRs from polymer samples with a suitable set of calibration standards. Despite the accomplished advances in mass spectrometric analysis of

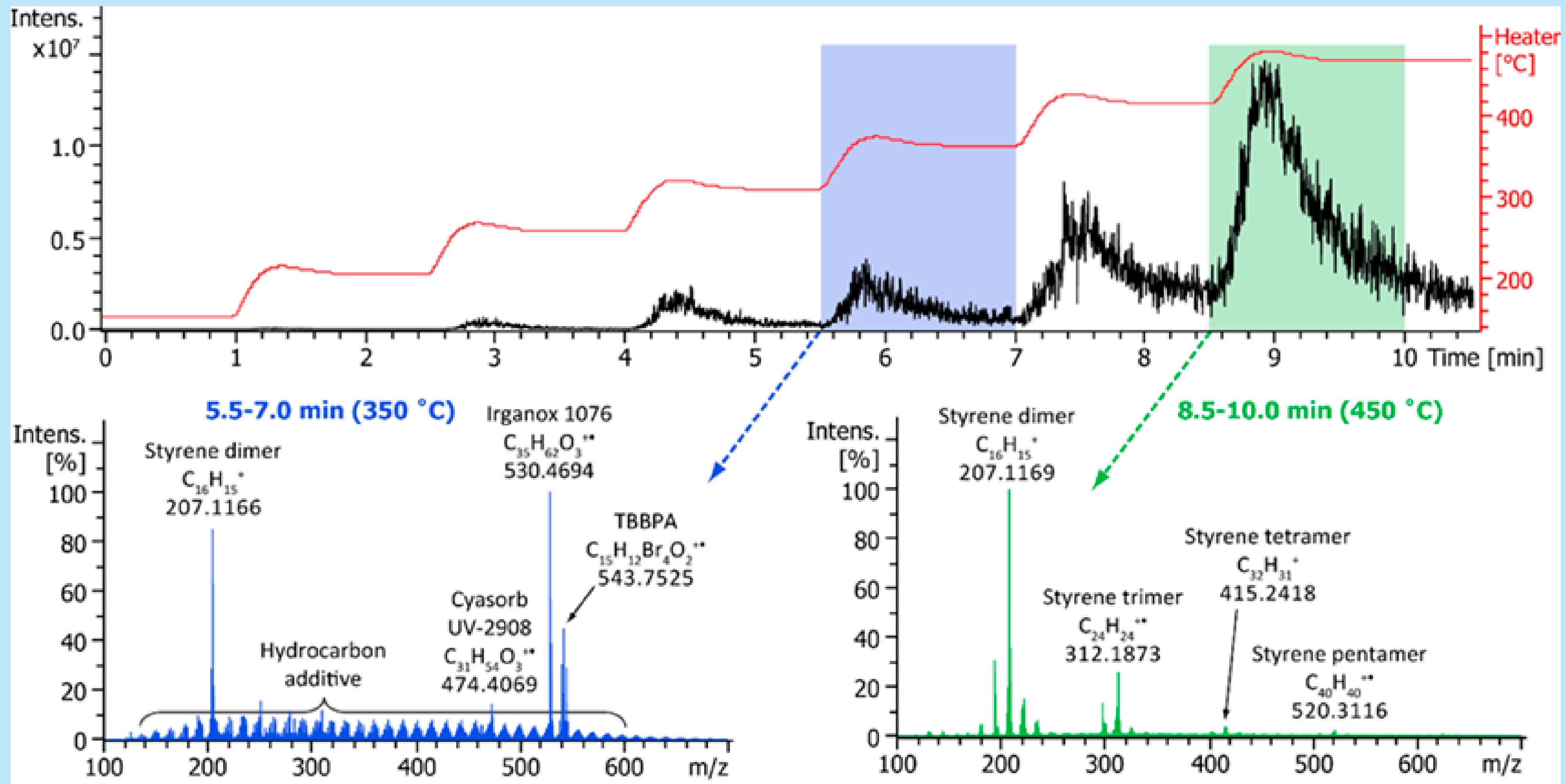

Figure 5. Temperature-programmed DIP-APCI Q-TOF mass spectrometric measurement of a HIPS sample containing TBBPA as a fire retardant. The top panel shows a TIC obtained using a vaporizer temperature program ranging from 150 to 450 °C. The bottom panels present averaged mass spectra obtained within time frames of 5.5–7 min (left) and 8.5–10 min (right), corresponding to temperatures of 350 °C and 450 °C, respectively. Auvinen et al., unpublished data.

BFRs directly from plastic samples, it must be emphasized that traditional solvent extraction followed by GC-MS and LC-MS analysis is still often required. Generally, these chromatographic methods provide the most accurate quantitative determinations.

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DEMON-STRATOR CASES:

rpolymer sourcing, characterisation, re-treatment and engineering

Demo 1 – rPC/ABS for automotive interior aesthetic components

Sourcing, characterisation and recycled content

Jani Pelto, VTT

ABS recyclates are available from styrenics feedstocks collected by the companies dismantling electrical equipment (WEEE stream). The ABS is sold either as flakes or homogenized granulates. The latter granulated product has thus experienced one melt processing cycle, which can be regarded both as an advantage and a disadvantage depending on the further processing route. On the one hand, the flakes have avoided thermal degradation caused by the homogenization step at the recycler, on the other hand they are not directly useful for converters without successive compounding.

Re-granulated ABS from the recycler has already upgraded properties for production, for example, it has been already well melt-filtrated, and may contain new additives, such as extra thermal- or UV-stabilizers, custom colou-

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"Recycled ABS and PC offer sustainability, but require careful processing."

ring, chain extenders or impact modifiers. Still, compounding companies can benefit from making the above-mentioned steps in their own facilities and therefore buying the flakes from the recycler.

PC is an important technical plastic which is less available from recyclers. It is usually found in mixed streams together with Styrenics stream, polyamides, polypropylene and even PVC etc. Recovery from mixed streams requires extensive sorting and decontamination additives as PC is particularly prone to property losses by hydrolytic degradation in the presence of even small traces of amounts of contaminants, such as halogenated flame retardants, PVC and residual moisture. Technically superior quality and less mixed rPC is available from post--industrial waste from processors of blow moulded containers and bottles, impact resistant protective gear, injection moulded or automotive parts and optical components, for example. The re-grinded post-industrial rPC material can be applied as such (100%), compounded with small percentage of primary PC and suitable additives (usually targeting for optical transparency), or blended with other polymers (PET, PBT, ASA, ABS) into high-performance resins used in automotive and electrical appliances. In favourable cases the properties of the primary resins (PC or PC-blend) can be reached or even exceeded with materials containing rPC.

It is technically possible to apply >85% recycled polymer (PCR) in the plastic formulation (rABS, rHIPS, etc.) with selected and extremely well-sorted streams. To be able to best control the variability of end-properties, it is good practice to combine materials from Post-Consumer Recycling (PCR) with raw materials from Post-Industrial Recycling (PIR) streams, if such streams are available.

An additional aspect when applying high recycled content (>50%) is to consider the fate of the plastic with the recycled content: it is not the same to use recycled plastic in fast moving packaging versus long lasting plastics parts in equipment, for example. There, it is wise to think of the lifespan of the corresponding plastic part, and possibility of the second life (or the end-of-life by feedstock recycling or energy recovery). Inevitably, polymers are degraded in every melt processing cycle. This is especially true for post-consumer waste materials which have undergone significant aging and degradation before entering the recycling facility. Therefore, mixing with (new) primary materials (technically at around 30-50% is used), or near-primary quality post-industrial feedstock is often seen at every mechanical recycling cycle. This procedure is also to avoid accumulation of highly degraded polymers entering the mechanically recycled plastics if the material will experience more than one (two or more) cycles in closed-loop recycling.

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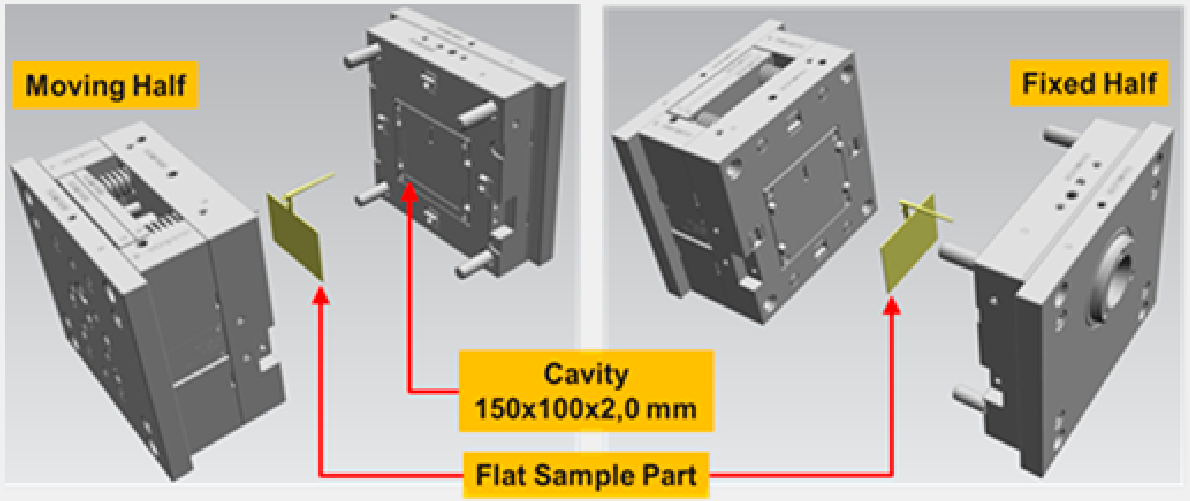
Pre-treatment and engineering

Beñat Madariaga, Maier

The results from the characterization tests show that the pre-selected commercial recycled PC/ABS materials have a general behavior that seems to be adequate for the Demo 1 Fascia application.

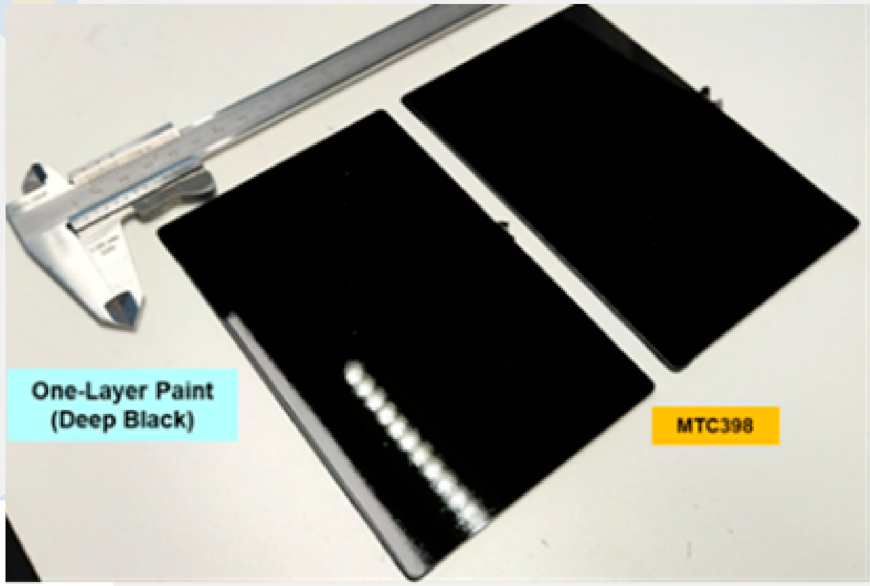
Injection molding is the technology commonly used to produce PC/ABS parts for the automotive industry. Injection molding of 2D sample parts (120 x 100 x 2 mm3) in a prototype mold are carried out to define the optimized processing window (melt temperature, mold temperature, injection speed) for each material under evaluation.

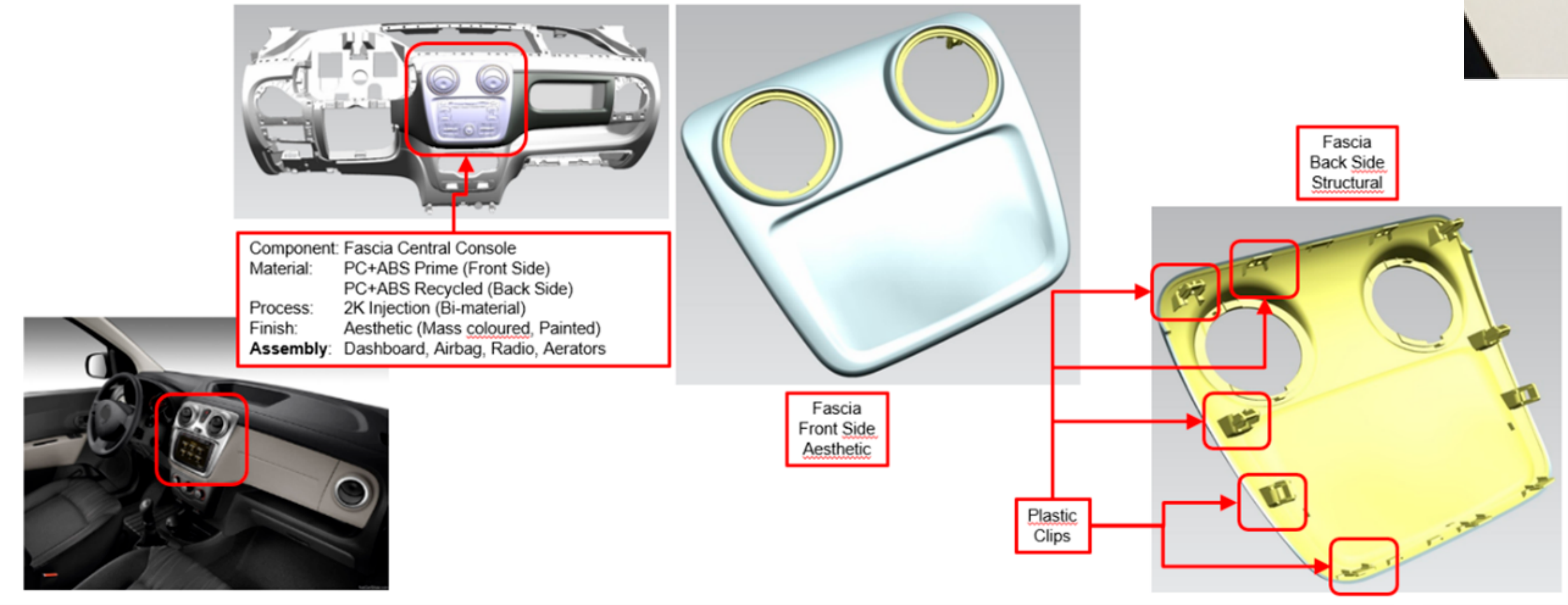


After that, aerographic painting of 2D sample parts is done, using different paint formulations (One-Layer Paint, Tri-Layer Paint). Preliminary functional validation tests are done to evaluate the chosen polymer formulation (visual aesthetic evaluation, color, gloss, initial adhesion, adhesion after immersion in water, high-pressure washing).

DEMONSTRATOR CASES

With this best suitable polymer formulation, a larger batch of rPC/ABS is produced for 3D-2K injection moulding tests with the real production mould. The parts are decorated in the same way to evaluate differences between recycled material versus primary one.





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LCA results

Julia Cilleruelo Palomero, GreenDelta

The following figures and table show the system boundary of Demo 1, as well as the normalised LCA results, Circularity scores and plastic littering risk associated.

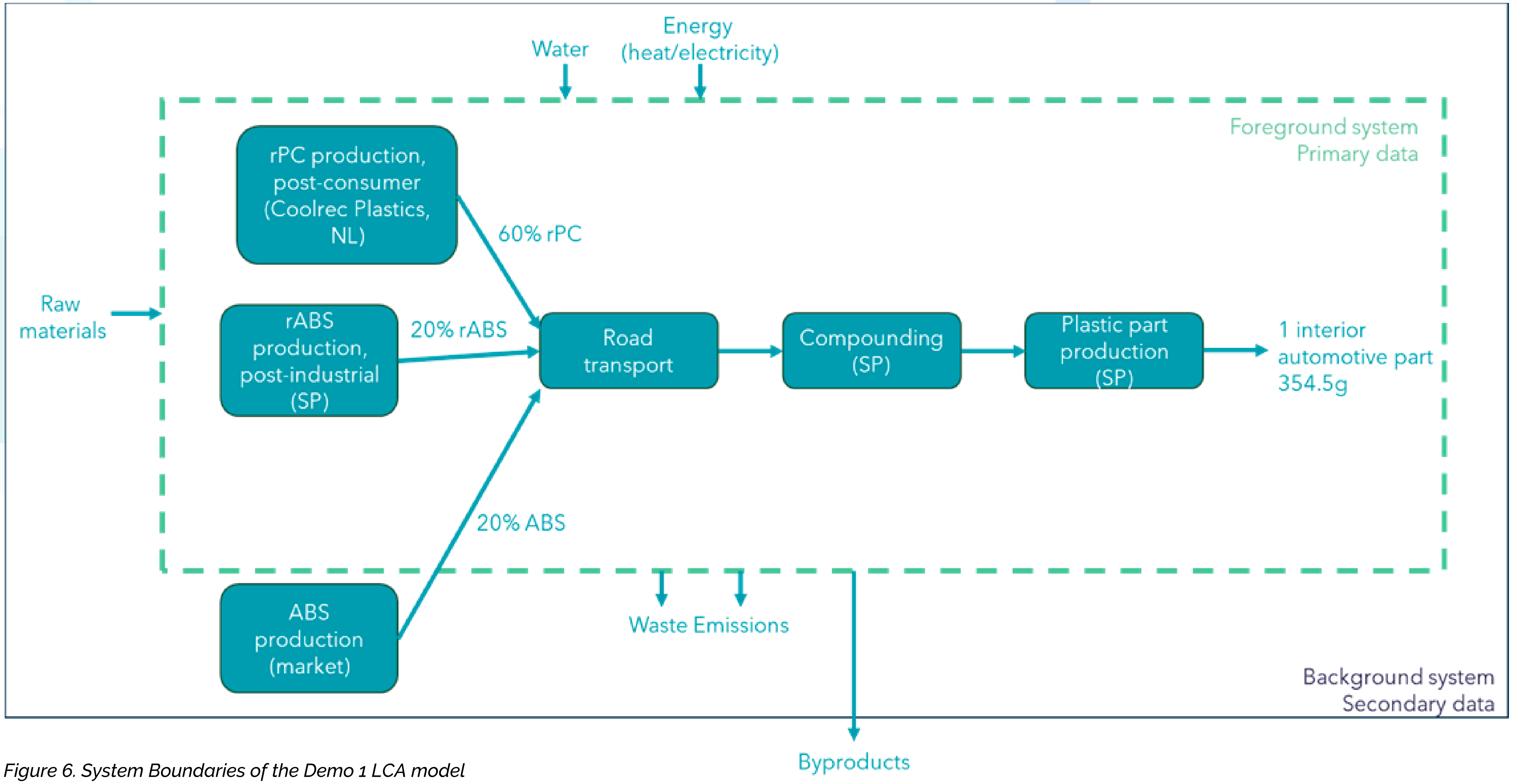

Figure 6. System Boundaries of the Demo 1 LCA model

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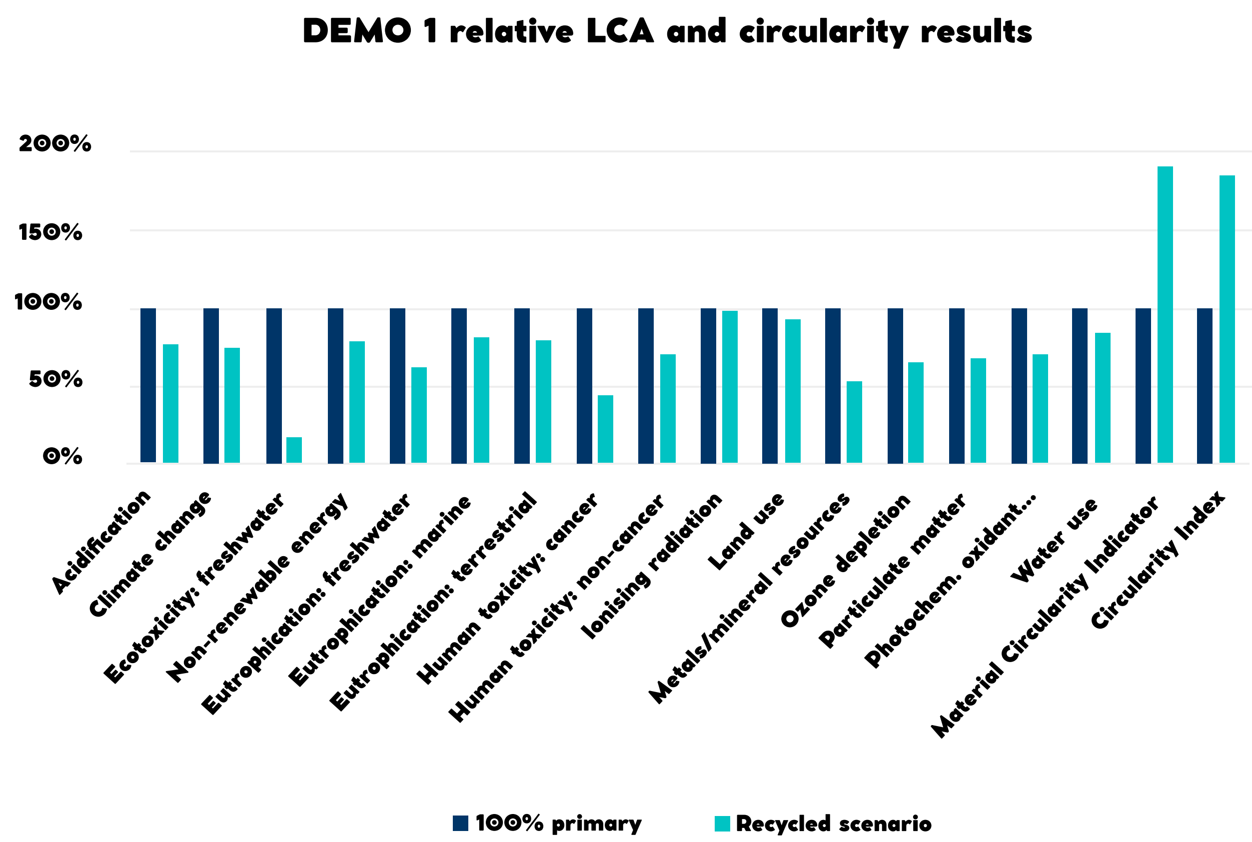

Figure 7. Demo 1 relative LCA and circularity results

Impact categories	100% primary	Recycled scenario	Unit
Climate change	5.03	3.68	kg CO2-Eq
Plastic littering risk	0.0070	0.0559	kg

Table 3. Demo 1 carbon footprint and plastic littering risk results

All LCA Impact Categories show promising improvements with the recycled scenario. These go as far as 84% improvement for Ecotoxicity (freshwater) impacts. Also worth noting is 48% less extraction in metals and minerals resource category, 27% less impact in Climate Change, and 22% less fossil resource extraction.

Specifically looking at Climate Change, the heaviest impacts come from the electricity used during part production, with around 58% of the total impacts, followed by the raw material mix, with around 40% of the impacts. Substituting PC by rPC completely and ABS with half rABS reduces the impact of the raw materials from 2.02kg CO_2 eq. to 0.67 kg CO_2 eq. Improvements between the 100% primary scenario and the recycled scenario were 5.03 kg CO_2 eq. to 3.68 kg CO_2 eq. per item.

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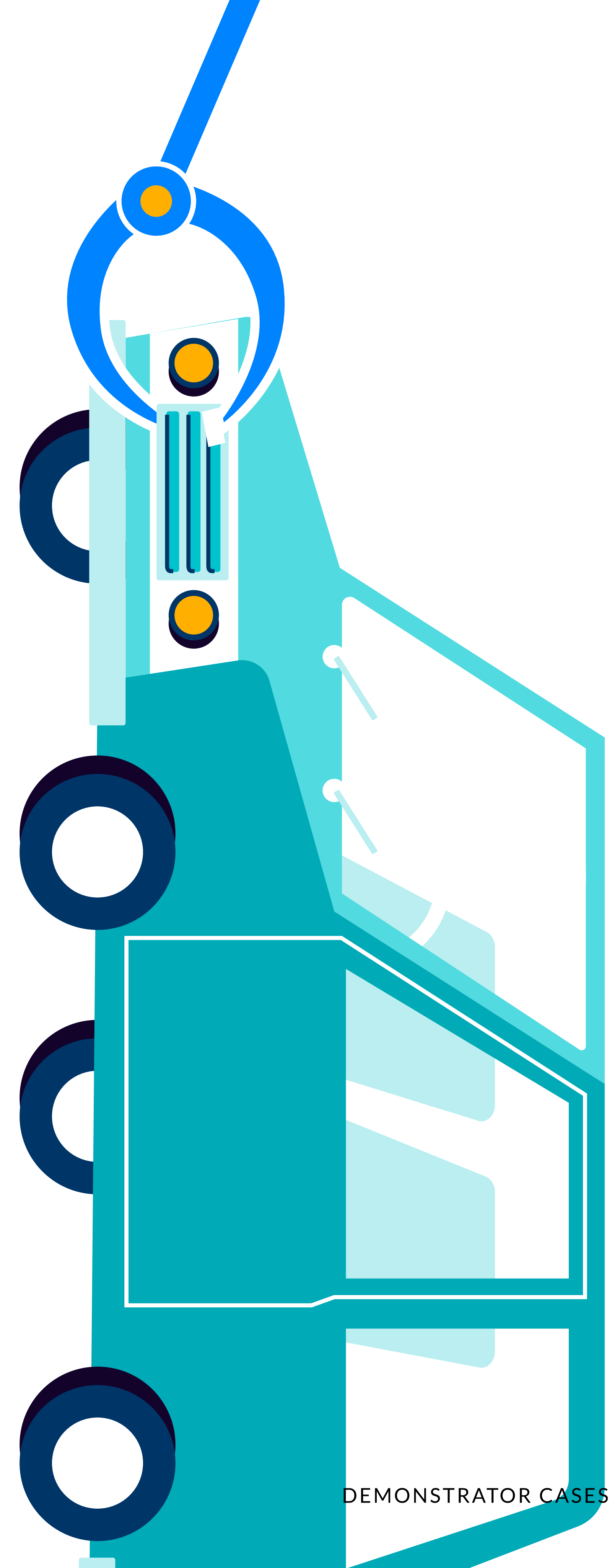
As electricity in part production is also seen as a hotspot for environmental impacts, the use of green energy should be considered to lower the environmental burdens of the system. Another thing to keep in mind is the transport of the recycled content, which could have a relative high contribution to the recycled plastic footprint. Sourcing local recycled contents is preferred.

There were also big improvements in the circularity scores, where the total energy required to produce the part was decreased by around 60% and the primary material used was also decreased by around 40% in the recycled scenario.

Also in circularity, increasing the life span (or number of uses) of the 100% primary part by 50% would arrive to the same circularity score (MCI) as the part with recycled content. This could be achieved, for example, by reusing the part in the production of new vehicles. Similarly, if the part with recycled content has a worse performance (<30% lifetime or number of uses), the MCI score goes back to that of the 100% primary part, highlighting the importance of having a recycled part that has at least the same quality as the 100% primary plastic part. In this case, as the plastic part is inside the car, it should last at least the life of the car and beyond.

Regarding plastic littering risk, it is considerably higher in the recycled scenario (70% higher) due to a very high percentage of recycled plastic used (80%) in this part. This is due to the methodology counting for a high risk of littering in recycling processes.



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Demo 2 – rPP/ EPDM for automotive cooling circuits

Sourcing, characterization and recycled content

Ainara Telleria, Cikatek

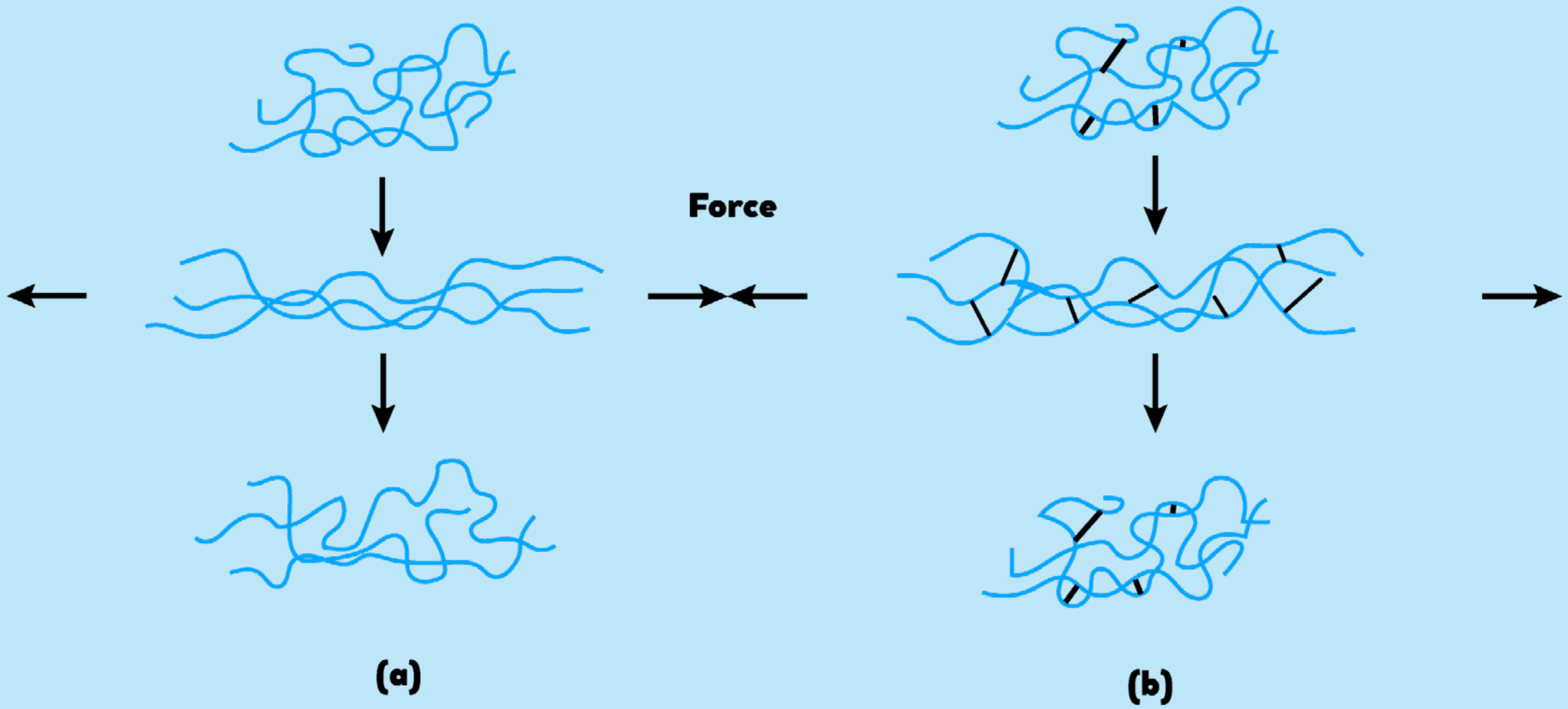

Figure 9. Difference between (a) Thermoplastic and (b) Elastomer polymer chains.

TPV is a material that combines the properties of rubber and thermoplastic phases. The rubber phase is the soft phase, which gives the elastic and mechanical properties to the TPV and the thermoplastic phase is the hard phase, which gives the melt processability. A wide range of TPVs can be obtained depending on the type of rubber and thermoplastic used but the most common one is PP / EPDM blend that contains EPDM particles dispersed in a continuous PP phase.

Recycled material can be introduced in a TPV formulation in two ways, using rPP or rEPDM.

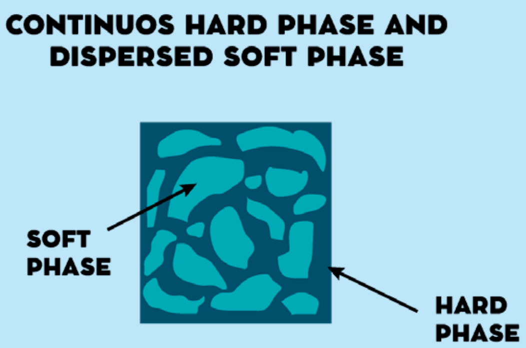

Figure 8. EPDM/PP cured blend (TPV) morphology.

These recycled components can be used in combination with usual raw materials.

PP is one of the most widely used thermoplastic polymers, making rPP relatively accessible in the market. An accurate analysis for the selection of the material is essential to obtain the desired results. The fluidity of the material and the ability of liquids to flow is a very important property that needs to be controlled. The fluidity indicates if a material can be processed using a certain technology (injection moulding, extrusion, blow

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moulding...) and it influences in the production efficiency, quality and performance. The fluidity of rPP can vary depending on whether it is post-consumer or post-industrial material. Post-consumer rPP tends to have more contaminants, making it less uniform, while post-industrial rPP is typically cleaner and may have more predictable processing characteristics.

The recycling of **EPDM** is more complex than that of a thermoplastic material because vulcanized rubber cannot be easily melted and reshaped like thermoplastics. EPDM is vulcanized during its manufacturing process creating a three-dimensional network with the polymer chains, which makes it more durable but more difficult to reprocess. A devulcanization process is necessary to break the bonds of the vulcanized network and obtain EPDM that can be processed again.

Devulcanization of EPDM can be achieved with the high shear generated inside an extruder, where the chemical bonds are broken by the effect of the applied mechanical stress.

Recycled content (%)	Tensile Strength (MPa)	Elongation at break (%)	MFI (g/10min)
0	13.7	440	2.4
18	14.7	496	10
23	14.0	422	14
30	12.9	467	21
36	13.3	510	30

Table 4. Properties of formulations with different recycled content.

The recycled materials used in this project were sourced through different companies. rPP comes from post-industrial material recovered from food cans, sourced from a local Spanish recycled material supplier whilst rEPDM comes from hoses collected from Cikautxo's factory (post-industrial). These recycled materials were introduced in TPV formulations together with the primary materials. The properties obtained with the mixtures with different recycled content are shown in Table. The 23% recycled content row shows the chosen option.

It is observed that as the recycled content increases, the value for tensile strength decreases and the value of the Melt Flow Index (MFI) increases significantly due to the high fluidity of the material.

MFI is an indicator of the fluidity of the material, it is measured by weighing the material that flows through a specific sized die, under a load and at a certain temperature in 10 minutes. A higher MFI indicates greater fluidity, the material flows more easily, while a low MFI indicates that the material is more viscous and flows more slowly.

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Pre-treatment and engineering

Ainara Telleria, Cikatek

Extrusion is the technology commonly used to produce continuous profiles, pipes and sheets. It is influenced by the fluidity of the material, affecting factors like output rates and dimensional consistency. This technology requires a material with medium fluidity, if the fluidity is too low (high viscosity) the material may have difficulty flowing through the die and if the fluidity is too high it does not have enough consistency to flow.

Figure 10. Extrusion of TPV material

"Extrusion requires balanced fluidity for consistent, high-quality recycled material processing"

Figure 11. DEMO 2

Pipes with 18% and 23% recycled material were extruded with adjustments on the processing conditions (decrease the temperature and the line speed) and using suitable dies. It wasn't possible to obtain recycled contents greater than 30% for the extrusion of the pipes due to the high MFI values. In addition to changing the processing parameters, additives like fillers or compounds to decrease fluidity would be needed for the extrusion of materials with higher recycled content.

Straight pipes are obtained after the extrusion, and a shaping process through thermoforming is needed to reach the final product.

In this last step, the pipe was placed in a tool with a specific form for which the fluidity/consistency of the material is very important. Materials with high fluidity may cause superficial defects due to the contact between the tool and the pipe. On the other hand, too low MFI can make the material difficult to form.

LCA results

Julia Cilleruelo Palomero, GreenDelta

The model and results are shown in the following figures.

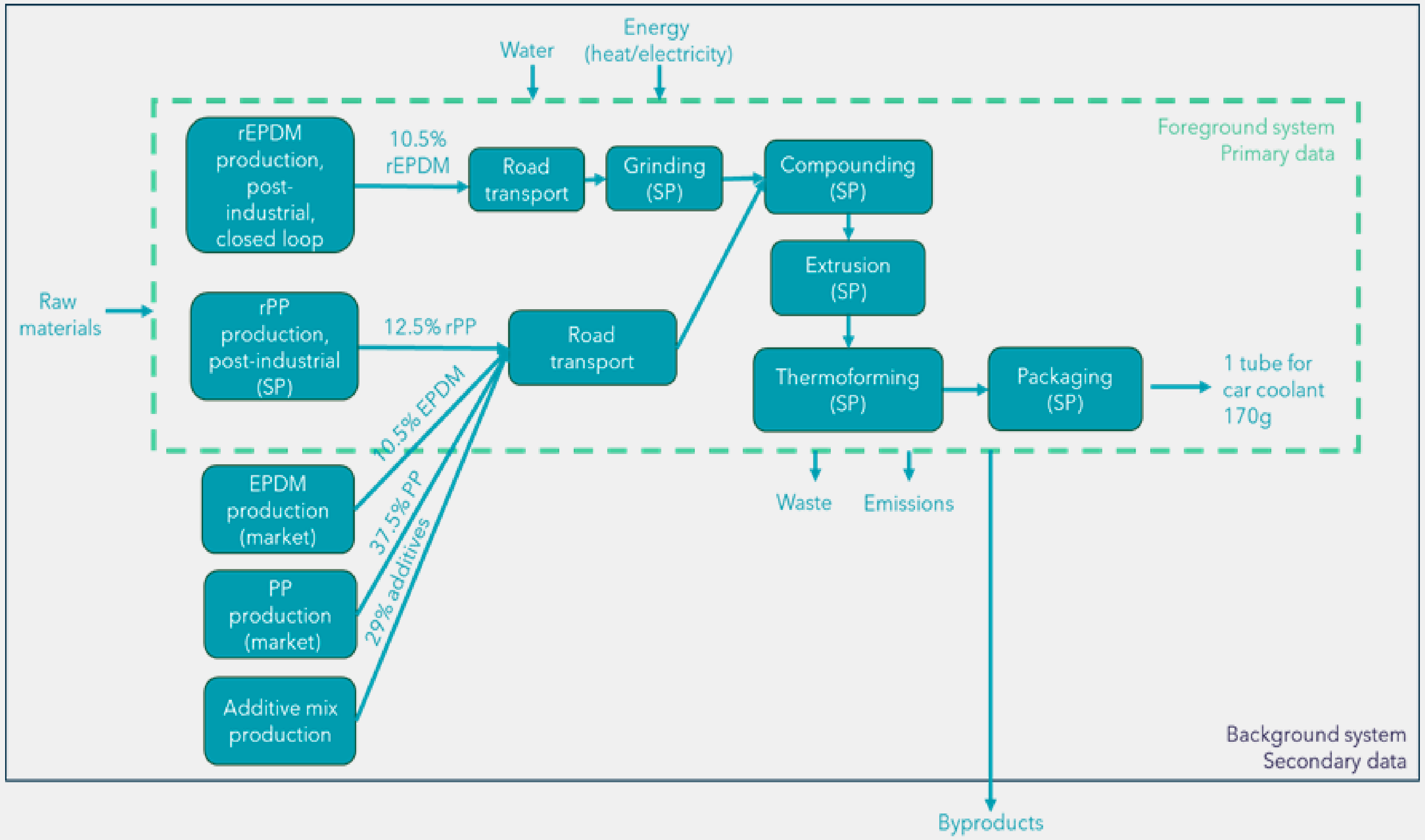

Figure 12. System Boundaries of the Demo 2 LCA model

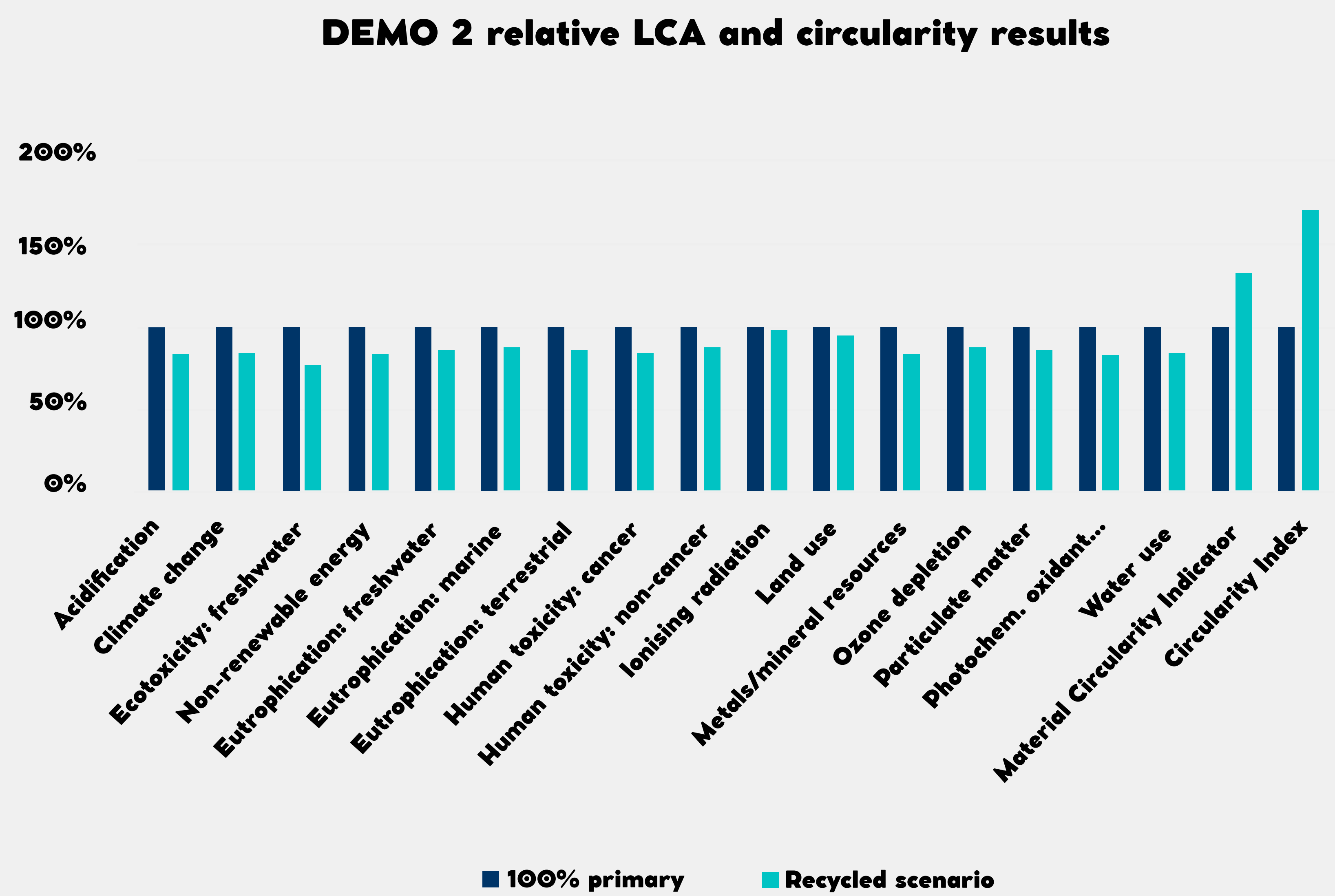

Figure 13. Demo 2 relative LCA and Circularity results

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Relative LCA and Circularity results for Demo 2

Impact categories	100% primary	Recycled scenario	Unit
Climate change	1.18	1.05	kg CO2-Eq
Plastic littering risk	0.00917	0.00906	kg

Table 5. Demo 2 carbon footprint and plastic littering risk results

> "Recycling improves environmental impact, but performance and circularity must be balanced"

The recycling scenario improves by around 10% to 20% in nearly all LCA Impact Categories, with a maximum of 19% improvement in the category Ozone Layer Depletion, and 11% improvement in Climate Change category.

Other environmental hotspots aside from the plastic material footprint are the cardboard box used for packaging and the natural gas burned during thermoforming. A more efficient packaging is recommended to be investigated as well as alternative energy sources for thermoforming.

Circularity is also benefited from the recycled content scenario, with around 13% less total energy required to produce the part, and around the same decrease for total waste produced and primary material.

Care should be taken with the performance of the recycled part, as a 10% decrease in performance already gives a worse MCI circularity score compared to the 100% primary counterpart. The efforts of material circulation are counteractive to any compromise in lifetime or number of uses of the material.

Finally, results look positive for plastic littering risk, where there is no apparent increased risk in littering when using recycled content to produce the part. This is explained by the use of post-industrial waste for the recycled material, as it doesn't need a lot of processing to achieve high quality recyclates and therefore the probability of littering is decreased. Plastic littering risk indicator, in this demonstrator, is dominated by plastic scrap waste followed by packaging.

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Demo 3 – rHIPS for refrigerator liners for food-contact

Sourcing, characterisation and recycled content

Ana Rita Neiva, Coolrec

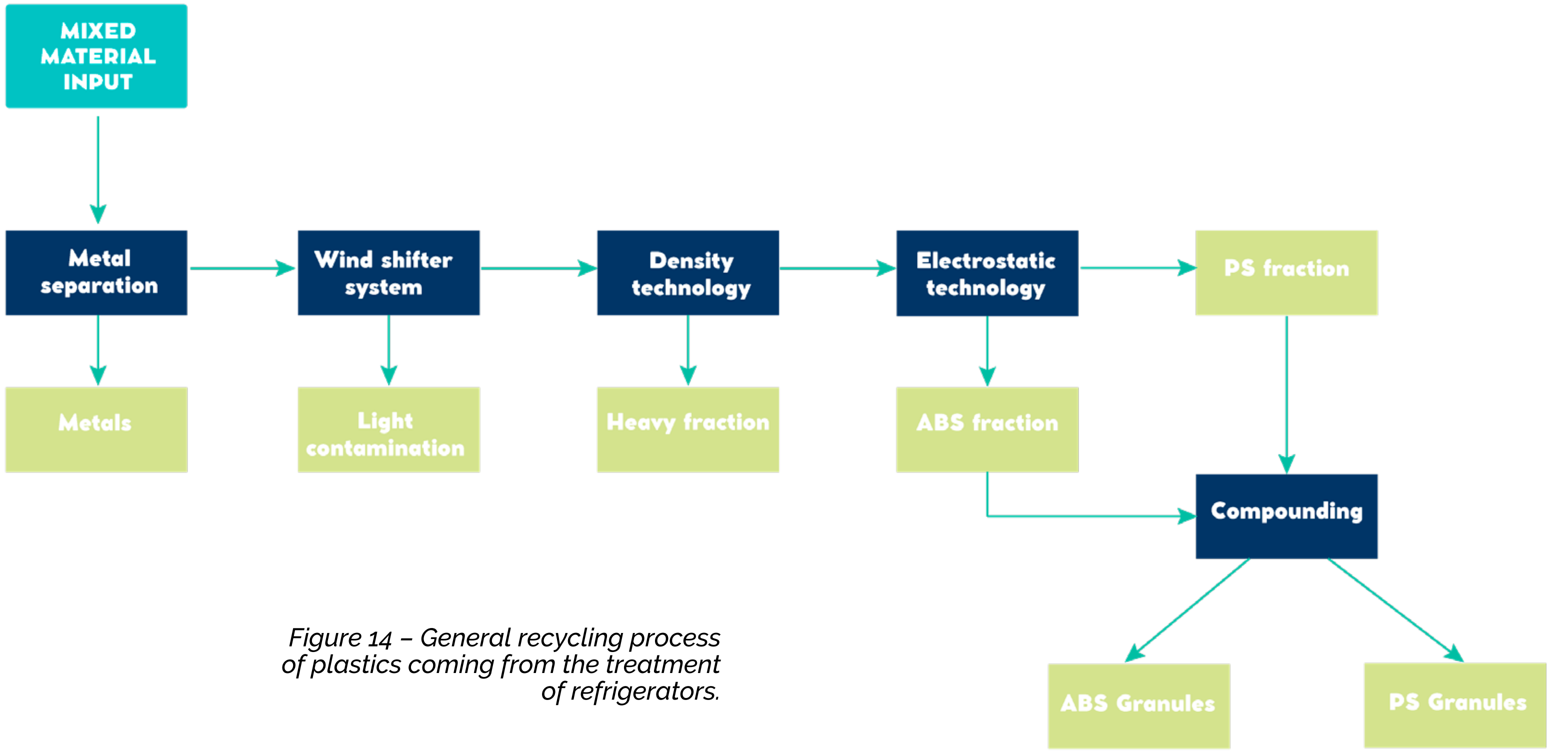

Figure 14 – General recycling process of plastics coming from the treatment of refrigerators.

rHIPS provided to the PRIMUS Project came from the direct recycling of refrigerators by Coolrec. Through Coolrec's industrial process, the refrigerators are unloaded in the lines, and first depolluted by removing oils and refrigerants, as well as removing capacitors and compressors. Through different mechanical processes, such as screening, shape separation, magnetic and Eddy current separation, valuable materials such as plastics, ferrous and non-ferrous metals are recovered.

The plastic fraction, still highly mixed with other materials is sent to further recycling processes at Coolrec Plastics. The first step is to remove the contamination of heavy fractions, such as ferrous and non-ferrous metals as well as the light fractions, such as foams, foils and wood using magnetic separation and wind shifters. To separate the plastic mix, density sorting is used by means of sink-float technologies. Plastics that contain high levels of hazardous substances are eliminated through this density process, in which heavier materials with a density higher than 1.10 g/cm^3 (including SVHC-containing plastics) will sink, and the polyolefins and styrenics will float. The separation of the styrenics is carried out by density sorting with densities of 1.00 g/ cm^3 and 1.05 g/ cm^3, which results in a fraction rich in PS. Using electrostatic technologies contamination present is reduced, and a rHIPS fraction achieves high purity, Figure 14.

The use of optical sorting for colour detection can also be used in the classification of recycled plastic.

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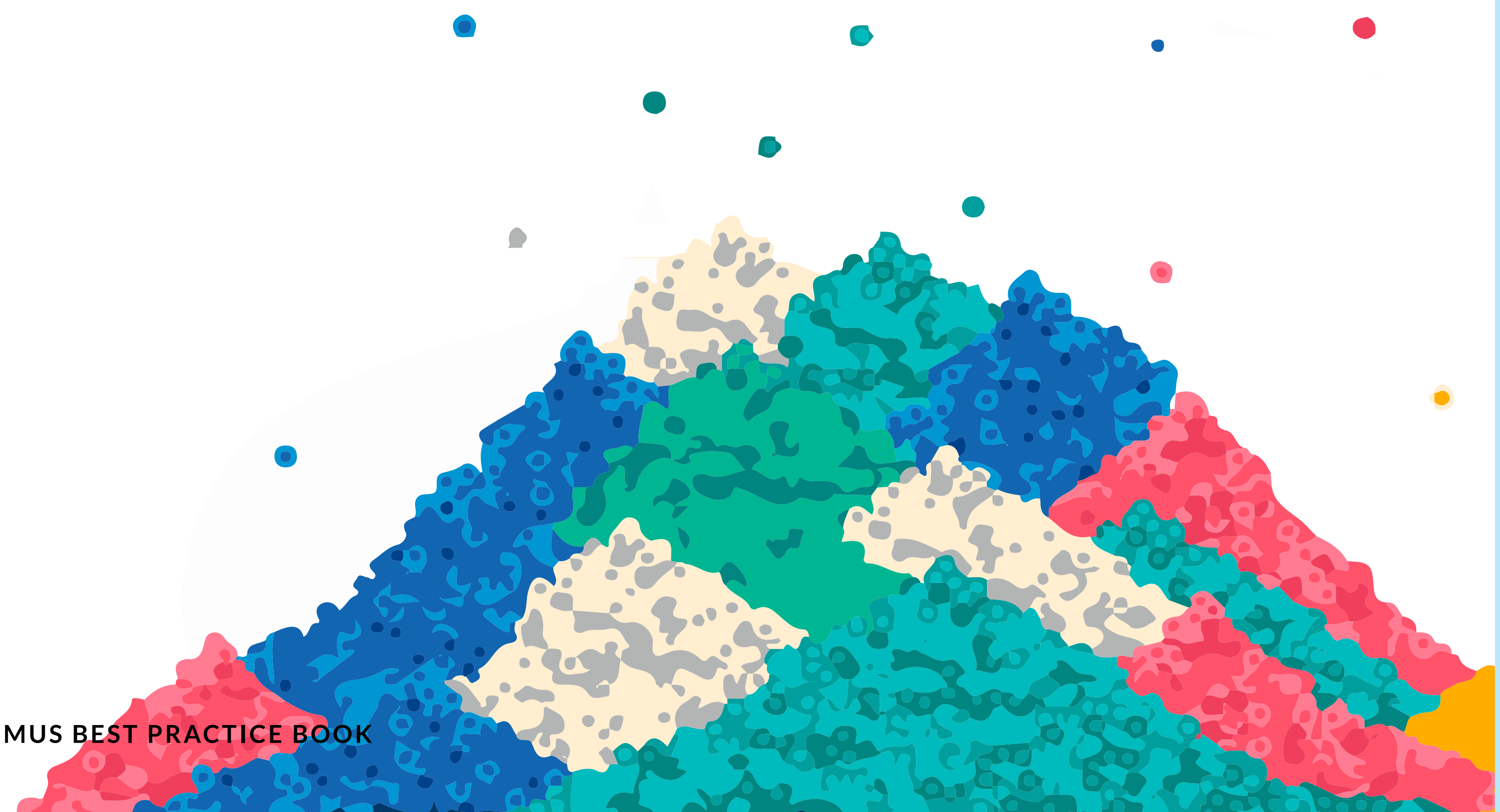
The combination of these technologies allows the separation of different types of plastics, including PS, and is crucial for obtaining a material with high purity, up to 95%. The other 5% are generally polymeric compositions in which ABS and PP are the main polymers present. Residual contamination from non-polymeric materials may be present and removed in a last compounding step, during extrusion processes in which filtration is used. Figure 15.

Figure 15 - rHIPS flakes (before extrusion) and granules (after extrusion).



Pre-treatment and engineering

Jani Pelto, VTT and Ana Rita Neiva , Coolrec

For the food contact application, the level of contamination of rHIPS must be carefully monitored both in the input and output batches of the mechanical recycling process cascade. The melt state extrusion-granulation process has an impact on the level of contamination finally present in the extruded granulates, so good control over the process conditions, melt degassing and melt filtering processes are needed. For example, efficient removal of cellulosic and other non-thermoplastic residues can be achieved with an appropriate filter mesh size, and thermal degradation avoided by using temperatures that do not reach more than 220 °C.

A suitable processing scheme for the PRIMUS rHIPS demonstrator was developed taking samples from different positions of the recycling process – both prior to extrusion and from extruded and melt filtrated pellets.

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The first assessment of the contamination present in the input and output batches was done acknowledging the fact that contaminants can originate from multiple sources, not only from the (separation and sorting) process inefficiency, but also from thermal degradation of PS (oligomers), environmental contaminations, substances naturally occurring in degradation processes, substances derived from foreign materials, or from unknown origin.

Specific migration testing of non-intentionally added substances (NIAS) was first conducted on ethanol test simulants, which is indeed a much harsher chemical condition than required for the migration test for refrigerator inner liner. However, based on these specific migration test results, it was possible to show that the major source for contamination in PRIMUS rHIPS samples was the aging and thermal degradation of the polystyrene and polybutadiene in the HIPS matrix. As a minor surprise, the set of substances and their concentrations found from the rHIPS were very similar to the ones found in the reference primary HIPS. Comparing to the first specific migration tests carried on rHIPS pellet and flakes, the internal GC-MS analyses (UEF) of the final thermoformed samples showed a similar set of NIAS (mainly styrene dimers and trimers). Later, the final thermoformed samples also passed the migration tests in an external accredited laboratory, which was the expected result based on the first assessment. To reach the compliance with the food contact regulations the following measures were taken:

"Controlling contamination and optimizing processing conditions are crucial for rHIPS food contact safety and compliance."

Processing melt temperatures were kept to the minimum (200˚C instead of 220˚C), the use of antioxidants and the use of primary HIPS to reduce the concentration of new oligomers and styrene monomers formation during processing. An efficient washing procedure was applied for the flakes. It turned out that a significant (70%) reduction of the measured PS trimers in the migration test it achieved already by pure water wash in a high intensity mixer in room temperature, followed by incubation of the rHIPS flakes at +100 ˚C/10h in an air circulation desiccant dryer. The drying conditions above glass transition temperature of the polymer are such that the volatiles were efficiently removed. Additional benefits, at least those that could have been seen in the migration test, were not gained by applying solvent wash with isopropanol or ethanol. This behaviour is not intuitively clear, as these solvents are penetrating deeper than water into the HIPS polymer matrix. However, it can be explained by diffusion of substances, as discussed in the following paragraph.

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It is known from literature and own experiments that the amount of the migrated substances quantified in the migration test represents only a small fraction compared to the oligomeric material existing (and remaining) in the bulk of the sample. As already noted, oligomers were found in similar quantities in the primary reference HIPS. This implies that the oligomers are not particularly mobile in the solid HIPS matrix, and that they can be extracted from the surface of the material even by cold water and friction wash. This observation is ultimately due to the low diffusion coefficient of many substances in HIPS, a distinguishing feature comparing to PE and PP. Hence it is also highly advisable to minimize the generation of more oligomers by using as mild as possible processing conditions and proper stabilization additive package for the rHIPS. Applying high vacuum during compounding is beneficially reducing the VOC content but has little effect on the poorly mobile and high boiling point compounds such as dimer, trimers and the other possible higher MW compounds.

Noteworthy, in normal context described in literature the term solid state decontamination (or "supercleaning") technology for HIPS (or PET) means incubation of the solid polymer in vacuum oven in elevated temperatures for prolonged times, thus allowing migration of the low molecular weight compounds and oligomers to the surface of the flakes - and evaporation into the vacuum. In this demonstrator case, a simpler approach was sufficient to reach compliance in the migration test.

The final formulation containing 70% of the rHIPS, compounded with 12% elastomeric impact modifier, stabilizer and 17% primary food grade HIPS was compounded using VTT´s instrumented mechanical recycling line, which is equipped with adequate melt filter and vacuum degassing. The compounded Demo 3 rHIPS material (70% recycled content) had comparable mechanical properties and very similar melt viscosity behaviour to the primary HIPS designed for this same application (fridge inner liner). The Demo 3 material could be easily extruded into a sheet and then thermoformed into deep 3D shapes using laboratory processing equipment available at VTT, Figure 16.

Figure 16. Thermoformed test samples containing 70% rHIPS (VTT). Compounding on VTT's cascaded mechanical recycling line. The rHIPS flakes for the compounding were from dismantled refrigerators (Coolrec)

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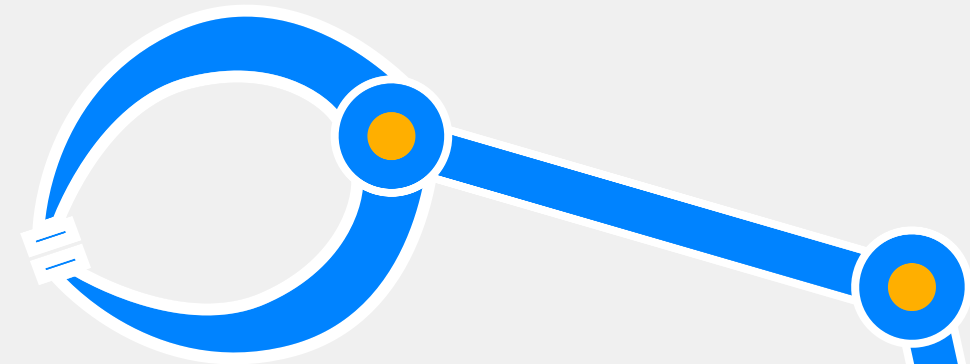
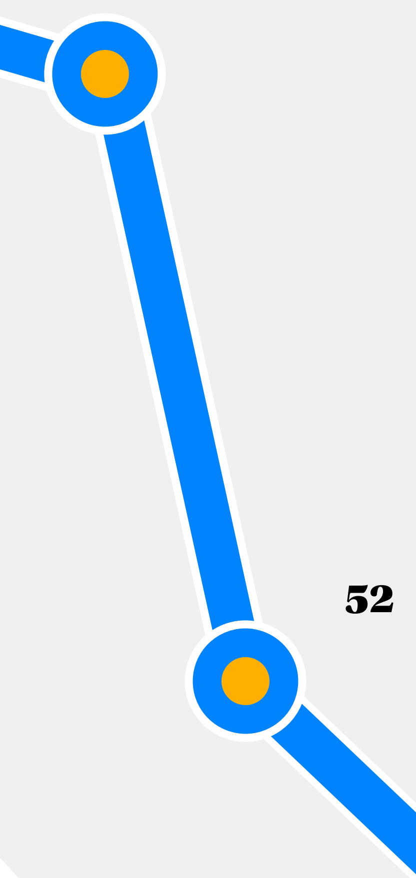
Guidance for food contact material

Mathilde Taveau, Plastics Recyclers Europe

To achieve food contact approval for recycled HIPS, recyclers have to submit an application in accordance with Regulation (EU) No 2022/1616. This regulation controls the use of recycled plastics in food contact materials, expanding upon previous legislation to accommodate advancements in plastic recycling technologies. The public guidance document (PRIMUS Deliverable 1.2) details the steps necessary for recyclers to obtain approval for food contact materials, including requirements on plastic waste collection, decontamination processes, and the difference between suitable and novel recycling technologies.

The PRIMUS project has generated data in the different sections required in the Regulation including contaminants analysis, migration testing and migration modelling. (LINK TO PU deliverables)





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DEMONSTRATOR CASES

LCA results

Julia Cilleruelo Palomero, GreenDelta

The detailed system boundary of Demo 3 is shown in the image on the side. The results are presented compared to a plastic part with 100% primary material and a table showing the carbon footprint and associated plastic littering risk of both the recycled and primary plastic scenarios.

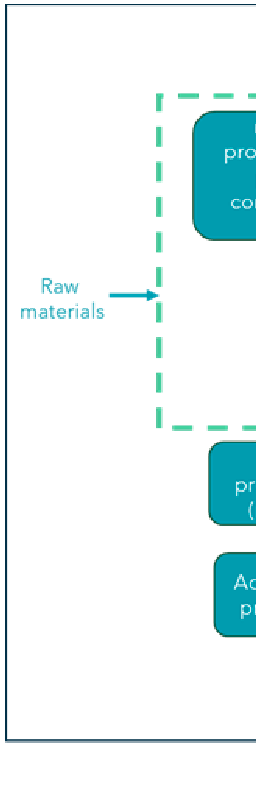

Figure 17. System Boundaries of the Demo 3 LCA model

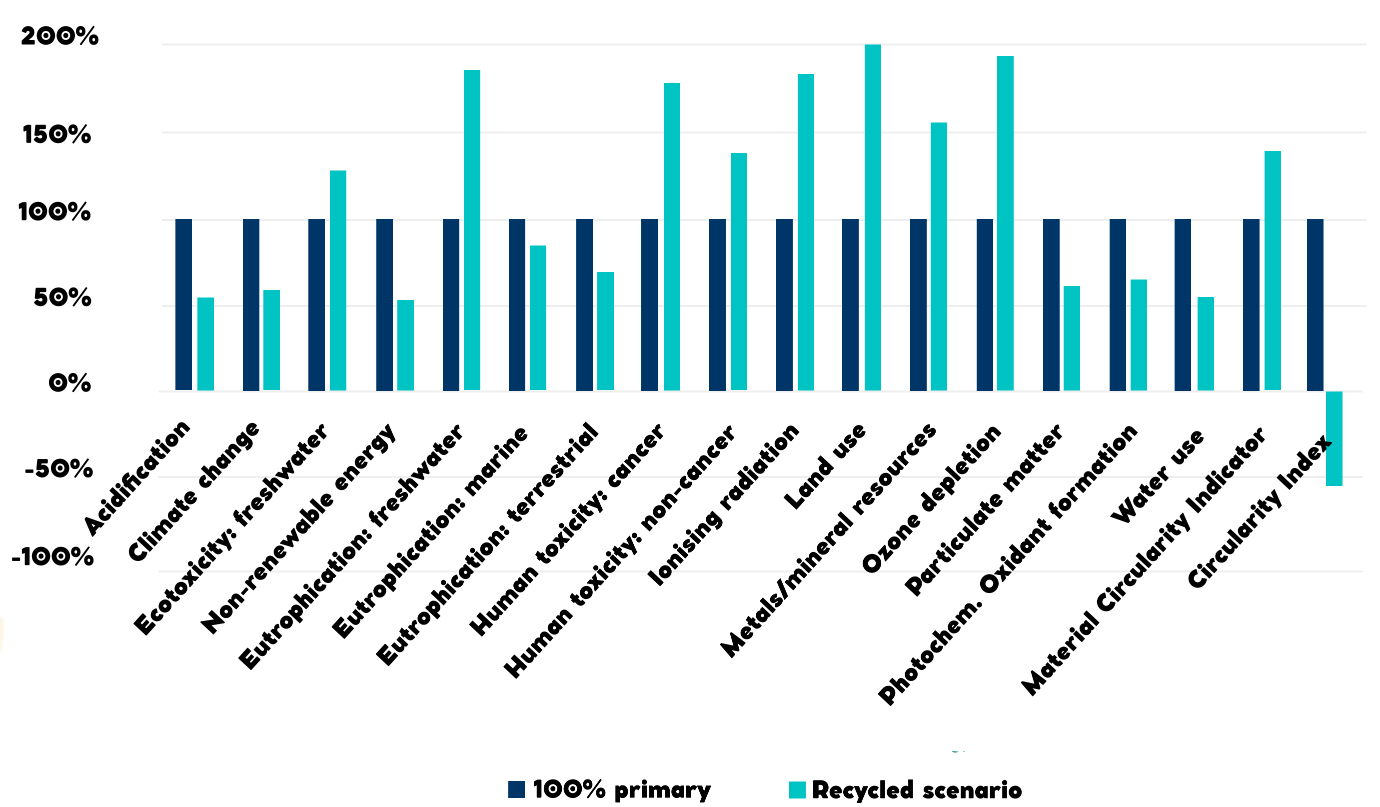

Figure 18. Demo 3 relative LCA and Circularity results

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Impact categories	100% primary	Recycled scenario	Unit
Climate change	4.08	2.36	kg CO2-Eq
MCI	0.127	0.178	No units, score from 0.1 - 1
CI	0.0187	-0.0103	No units, score from 0 - 1

Table 6. Carbon footprint and Circularity results for Demo 3

There is a 42% decrease in Climate Change with the recycled scenario, where the production of primary HIPS already accounted for 86% of the total impact. It therefore made sense to substitute this with rHIPS. The plastic compound mix decreases from a value of 3.84 kg CO_2 eq. to 2.15 kg CO_2 eq. per kg of mix.

Some Impact Categories, however, show an increase in environmental damage. Ecotoxicity, Human Toxicity, and Land Use are specifically affected by the big transport distance of recycled material between the Netherlands (recycler) and Finland ("manufacturer"). Eutrophication (freshwater), Ionising radiation and Ozone Layer Depletion are affected by the large amount of electricity used to produce the recyclates. Also, Resource use (minerals and metals) is negatively affected by the copper used in the electric grid network, and, as more energy is required in the recycled scenario, the effects on Resource use are more prominent. Finally, Eutrophication of fresh water is affected mainly by the use of nitrogen in the sorting of recycled content, as well as electricity used throughout.

Shorter transportation distance between recyclate production and use and green electricity in recycling processes will help damping higher impacts in Ecotoxicity, Human Toxicity, Land Use, Eutrophication (freshwater), Ionising radiation, Ozone Layer Depletion and Resource use (minerals and metals).

Unlike the other demonstrator cases, the total energy required and waste produced is worse in this scenario. This shouldn't be affected by the lab-scale of the demo case as the contribution mainly comes from the production of recyclates, which is already an industrialised system.

The large amount of electricity required in the production of recycled material is also responsible of the negative Circularity Index (CI) shown in the last rows of Table 6. This indicator shows worse results in the recycled content scenario.

There is a big change in the risk of plastic littering when the recycled scenario is considered. The highest amount comes from the production and transportation of rHIPS, however HIPS supply chain and the management of the waste from the part production are also relevant.

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Demo 4 – rEPDM for washing machine door seal

Sourcing, characterisation and recycled content

Ainara Telleria, Cikatek

Door gaskets from washing machines are 100% made of rubber and the majority of them by EPDM rubber. EPDM has excellent water and heat resistance; it can withstand temperatures up to about 150˚C without losing its sealing properties. It is also resistant to tear and to washing machine chemicals, including detergents, bleach, softeners and other cleaning agents.

To produce the door gaskets with recycled plastics, the first step is to produce the rubber mixtures containing those recyclates. In this project, the recyclates have been obtained from end-of-life washing machine door gaskets provided by Coolrec, making it a fully closed recycling cycle.

Figure 19. Washing machine door seals provided by Coolrec

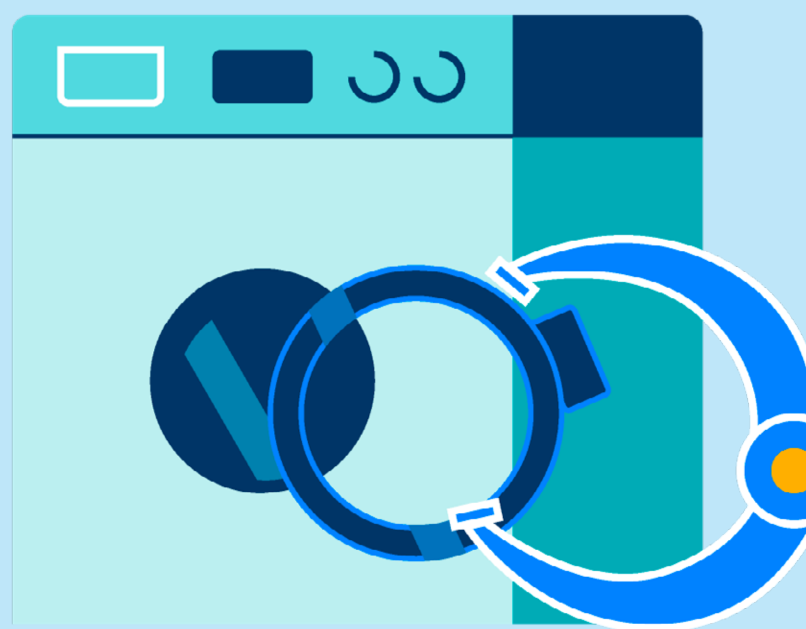

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Figure 20. Recyclate produced by grinding the end of life washing machines

The parts were cleaned in an industrial washing machine with hot water and detergent at 1% concentration to remove the hard particles like sand and other source of contamination like grease.

The next step was chunking the door gaskets to get particles of 4 mm to 5 mm. Finally, the chunked material was micronized to <0.25 mm with an equipment that compresses and cuts the particles. With this technology, particles with size < 0.25 mm were produced, increasing the surface area due to the irregular surface. This helps to have a low drop of mechanical properties in the final product containing recyclates compared to the ones that don't contain recyclates.

#sample	% of recyclate	ML for rheometric curve 5 min at 180°C	Hardness ShA	Tensile Strength (MPa)	Elongation at break (%)
Requirement	-	< 1,1	38±3	>8	>550
DM4-001	0	0,52	37	10,5	850
DM4-008	7	0,78	37	10,2	810
DM4-009	10	0,81	38	9,9	789
DM4-010	15	0,92	38	9,4	761
DM4-011	20	1,04	37	9,0	735

Table 7. Properties of formulations with different recycled content

5 EPDM rubber mixtures were produced with 0%, 7%, 10%, 15% and 20% content of the produced recyclates. The properties of the 5 produced mixtures met the defined requirements as shown in table above.

The viscosity of the mixtures is a crucial property for the injection moulding process and can be measured with the ML (minimum torque) value of the rheometric curve. It defines the resistance of the material to flow under applied pressure/temperature conditions and impacts on the mould filling, cycle time and in the quality of the final product. As it is shown in the table above, the ML value is higher as the recycled content increases. Higher viscosity materials require longer flow paths to ensure uniform filling while low viscosity materials need shorter cycle times because the material fills the mould faster and cools more quickly.

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Pre-treatment and engineering

Ainara Telleria, Cikatek

Injection moulding was used to produce the door gaskets. Injection moulding is one of the most widely used manufacturing processes and it is based on the melting of the material with heat before injecting it in the mould cavity. Once the mould is filled, the material is cooled and solidified to obtain the desired geometry.

Mixtures with 0%, 10% and 20% of recycled material were manufactured.

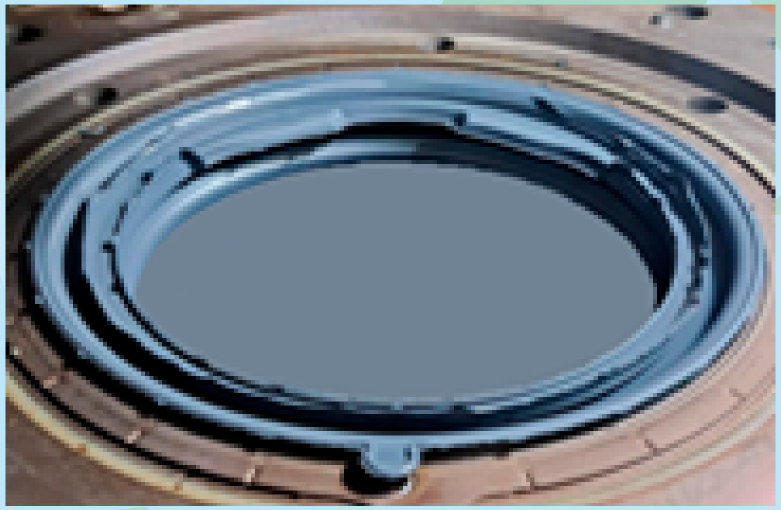

Figure 21. Part in the production mold

Only the production of parts containing 20% of recycled material was considered not satisfactory due to prevulcanization signs in the surface.

Figure 22. Prevulcanization marks in the surface of the part

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LCA results

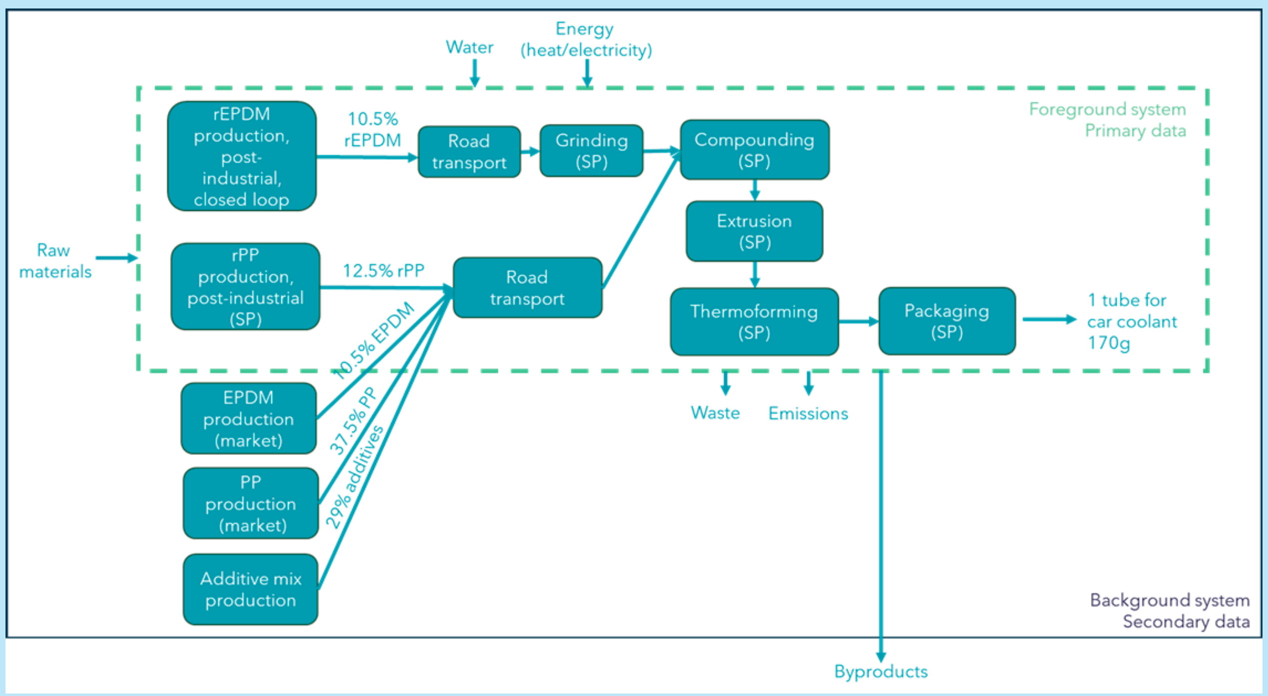

Figure 23. System Boundaries of the Demo 4 LCA model

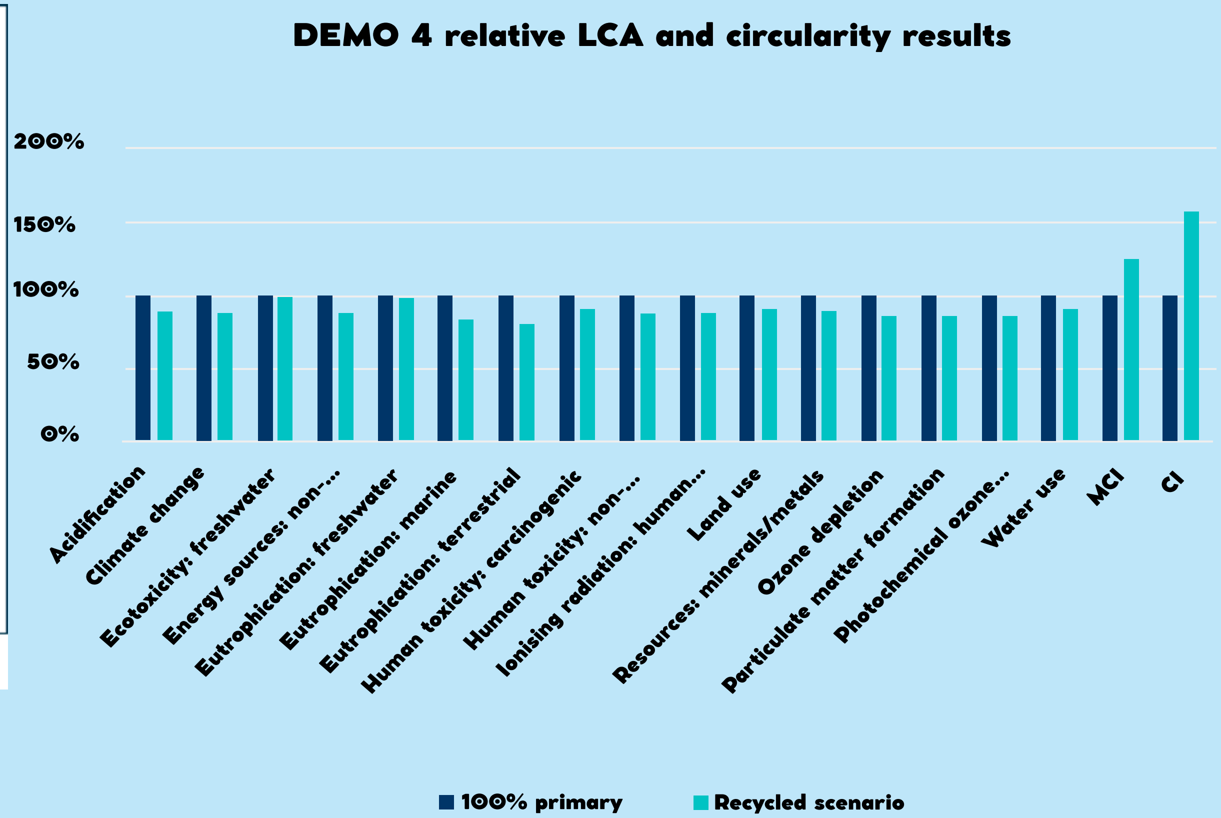

Figure 24. Demo 4 relative LCA and Circularity results

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Impact categories	100% primary	Recycled scenario	Unit
Climate change	3.15	2.77	kg CO2-Eq
MCI	0.180	0.226	No units, score from 0.1 - 1
CI	0.0494	0.0786	No units, score from 0 - 1

Table 8. Carbon footprint and Circularity results for Demo 4

Adding 10% rEPDM shows an improvement in all LCA and circularity categories, but small.

Even though paraffinic oil and kaolin make most of the compounding formula (67%), these only carry 8% (kaolin filler) and 3% (paraffinic oil) of the Climate Change impacts and similar in other impact categories, so it is good to focus on EPDM to reduce the environmental impacts of the plastic part.

With such small percentage recycled content, the performance (e.g. lifetime or number of uses) of the part cannot be compromised or else the improvements in the circularity score can decrease to a worse score than the primary scenario.

Trying to add more fillers and oil to compensate adding more rEPDM should be considered.

Packaging is also an important contributor to the environmental footprint, with 28% contribution in Climate Change impact category. Investigating on a more efficient use of the cardboard box, or thinner cardboard, etc. could be beneficial.

Introducing 10% rEPDM to the material mix increases the plastic littering risk from 0.0263kg litter probability per plastic part to 0.0356kg. The factors contributing to plastic littering risk come from rEPDM followed by waste plastic scrap that finishes in landfill and the carboard packaging.

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SOCIETAL PERCEPTION AND ENGAGEMENT

General public's perspectives over plastics

Maaris Raudsepp and Eve-Liis Roosmaa, Tallinn University

To effectively address societal concerns and promote the use of products with recycled content, it is crucial to understand the diverse attitudes and decision-making behaviours of consumers. Our secondary analysis of Eurobarometer (different waves from 2007 to 2019) and ISSP (International Social Survey Programme 2010, 2020) surveys led to a consumer typology that highlights varying environmental beliefs and attitudes towards plastic recycling. This typology was further refined through the original citizen and consumer awareness and acceptance of recycled plastics survey in 2023 in Spain, Germany, Finland, and Estonia, countries representing different welfare regimes, regulatory policies, and cultural contexts (D6.2 Report).

The findings reveal overall public environmental concern and behavioural commitment to recycled plastics, although with country variations. Respondents in all four countries generally prefer products made with recycled plastics due to their perceived environmental benefits.

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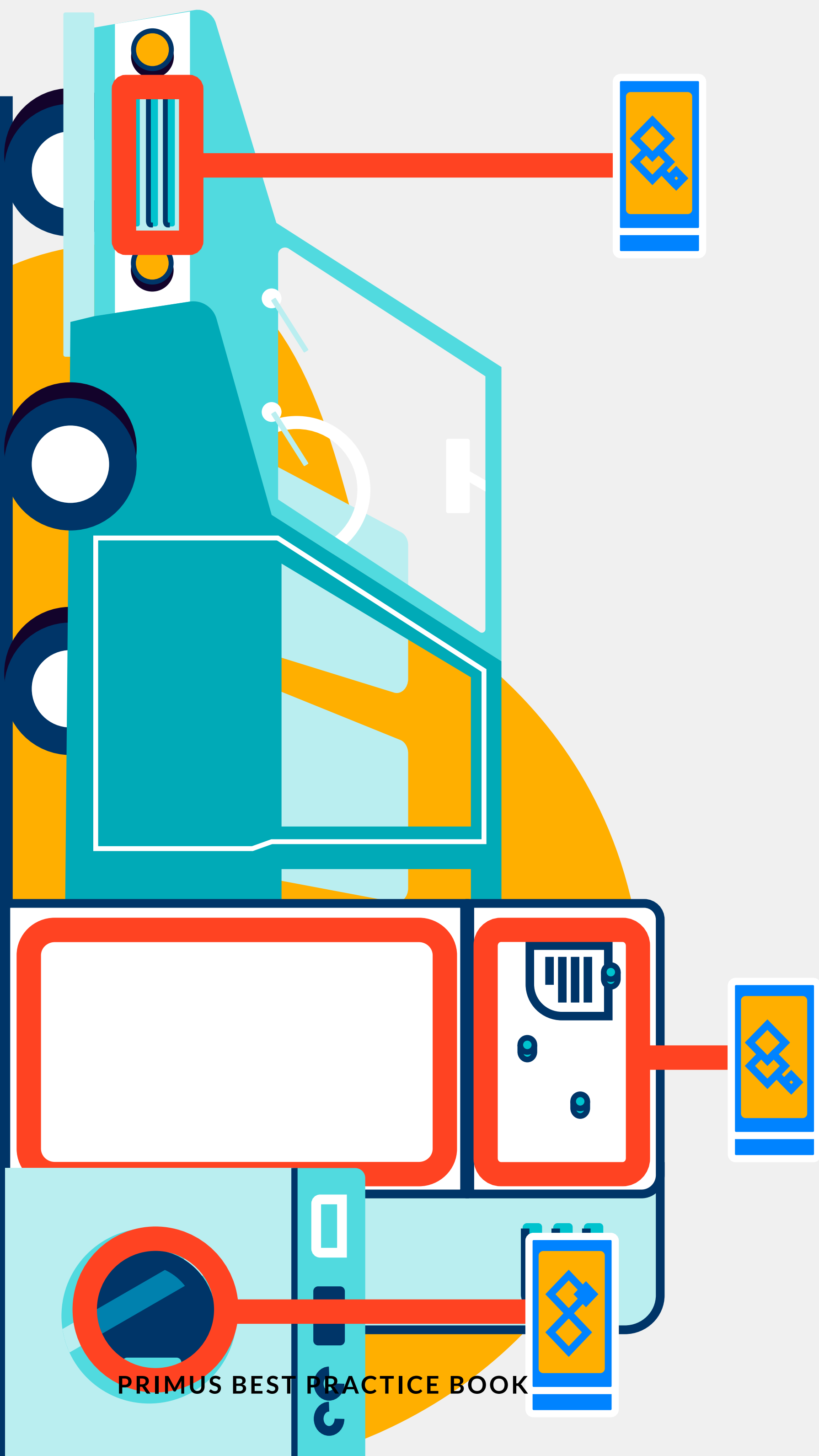

However, respondents in Estonia and Spain exhibit slightly greater uncertainty regarding these environmental advantages. Furthermore, a sense of agency (believing that one can play a role in protecting the environment) is rather high across all countries, but somewhat higher in Spain and Germany. While in Finland, for example, there is comparatively stronger belief that plastics recycling system works properly and is a way to combat plastic pollution and climate change.

Drivers to acceptance of recycled plastics include positive perceptions of safety and environmental friendliness, while barriers vary by country. Finland and Germany express higher confidence in recycled products, whereas Estonia and Spain show greater uncertainty about their experiences with recycled plastics that in turn might hinder acceptance. Overall, less than half of the survey participants (and even fewer in Spain) have no issues of concern regarding the use of recycled plastics compared to conventional plastics. Concerns relate mainly to health safety, followed by the lack of long-term studies on recycled plastics (somewhat more so in Estonia and Spain), and inadequate regulations or standards (particularly in case of Spain). Another barrier is relatively low awareness regarding recycled plastics, because considerable proportion of survey participants have difficulty to answer questions specifically about this material.

Analysis of open-ended responses indicate nuanced country-specific concerns. Consumers in Estonia and Finland show a need for increased awareness about recycled plastics, while consumers in Spain exhibits distrust in the recycling process, viewing it as potential greenwashing. Respondents in Germany and Spain also emphasise the environmental footprint of recycling, advocating for sustainable alternatives and a reduction of overall plastic consumption.

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To explore within-country variations, respondents were categorised into groupings based on environmental concern and agency, resulting in following consumer segments: Ecologically Committed, Fairly Concerned, Ambivalent/Hesitant, and Unconcerned/Sceptical. The Ecologically Committed consumer segment is characterised by a high level of environmental concern and willingness to invest in sustainable products, while the Unconcerned/Sceptical segment, often younger and less educated consumers, shows distrust towards recycled materials.

The study highlights drivers and barriers to recyclate acceptance across segments, emphasizing the need for targeted strategies that resonate with the unique values and lifestyles of different consumer personas. Effective communication and regulatory measures are essential to address public concerns, which vary significantly by cultural and national context. Tailored awareness campaigns aimed at sceptical or indifferent consumers, particularly younger and less educated individuals, can enhance acceptance and commitment to recycled plastics.

Overall, consumers lack sufficient information about plastic recycling, leading to some confusion and distrust. Raising awareness about regulations, the plastic lifecycle, innovative recycling technologies, and the ecological impacts of recycled materials is crucial for fostering acceptance and promoting sustainable practices.

Gender-perspective on plastic recycling

Eve-Liis Roosma, Tallinn University and Jonas Hoffmann, GreenDelta.

PRIMUS citizen and consumer study (2023) revealed considerable gender differences regarding environmental concern. Women are considerably more concerned about environmental issues and severity of plastic pollution, which according to the secondary data analysis is in line with other surveys addressing environmental attitudes, e.g. Eurobarometer, International Social Survey Programme.

Regarding barriers to recycled plastics acceptance, men are somewhat less concerned about any possible issues with the use of recycled plastics in comparison to conventional plastics and there are no differences in terms of toxicity worries or no sufficient regulations being in place to ensure recycled plastics are safe to use. Women tend to express only slightly greater concern over the

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health safety and lack of long-term studies about the impact of recycled plastics.

In terms of behavioral commitment to recycled plastics and purchase intentions, results are mixed. Both men and women consider choosing products made of recycled plastics instead of conventional plastics as an environmentally friendly action. Yet, for women environmental friendliness of a product is of more importance when purchasing for example a washing machine or refrigerator, but there are very small differences regarding the preference to buy home appliances or a car containing recycled plastics (women are just slightly more inclined to buy such home appliances, while men a car). Additionally, men are more willing to buy home appliances containing parts made up to 100% from recycled plastics, while there are no gender differences if the share of recycled plastics in a product would be smaller (5%-50%). However, rather high proportion of men and especially women are undecided on the matter, meaning they are not sure what exactly a certain content of recycled plastics in a home appliance means (e.g. in terms of safety or quality). Interestingly, men are less willing to pay more for a home appliance or a car containing parts made of recycled plastics, indicating that women have somewhat more trust towards this material. But women are again somewhat more uncertain of their purchase intentions regarding higher product prices. Overall, these results are consistent with the Eurobarometer 2014 which also indicated no significant gender differences regarding agreement to pay a little bit more for environmentally friendly products.

As part of our Social Life Cycle Assessment (LCA) process, we conducted an extensive literature review to identify existing data on the gender dimensions of plastic recyclates. Unfortunately, our search uncovered a significant gap in the current literature. However, we did find studies addressing gender-related aspects in the broader context of plastics. Notably, research conducted by WECF in collaboration with UNEP and GPA highlights the gender-specific impacts of harmful plastic additives on women, see https://sv.boell.org/sites/default/files/womenandplastics_1.pdf . These additives —primarily bisphenol A, phthalates, and polybrominated diphenyl ethers — are known for their bio-accumulative properties and potential to disrupt endocrine functions, As these additives are not chemically bonded to the polymers, they inevitably leach out, posing risks of exposure during the recycling of plastics. The PRIMUS project specifically investigates the debromination and removal of such additives.

The lack of data focused on the gender dimensions of plastic recyclates is compounded by the limited availability of gender-disaggregated research on workers' exposure to hazardous chemicals, particularly in low-income countries. However, one mitigation strategy to remove and decompose endocrine disrupting additives, like brominated flame retardants, from plastic had been developed within this project, see section 4.

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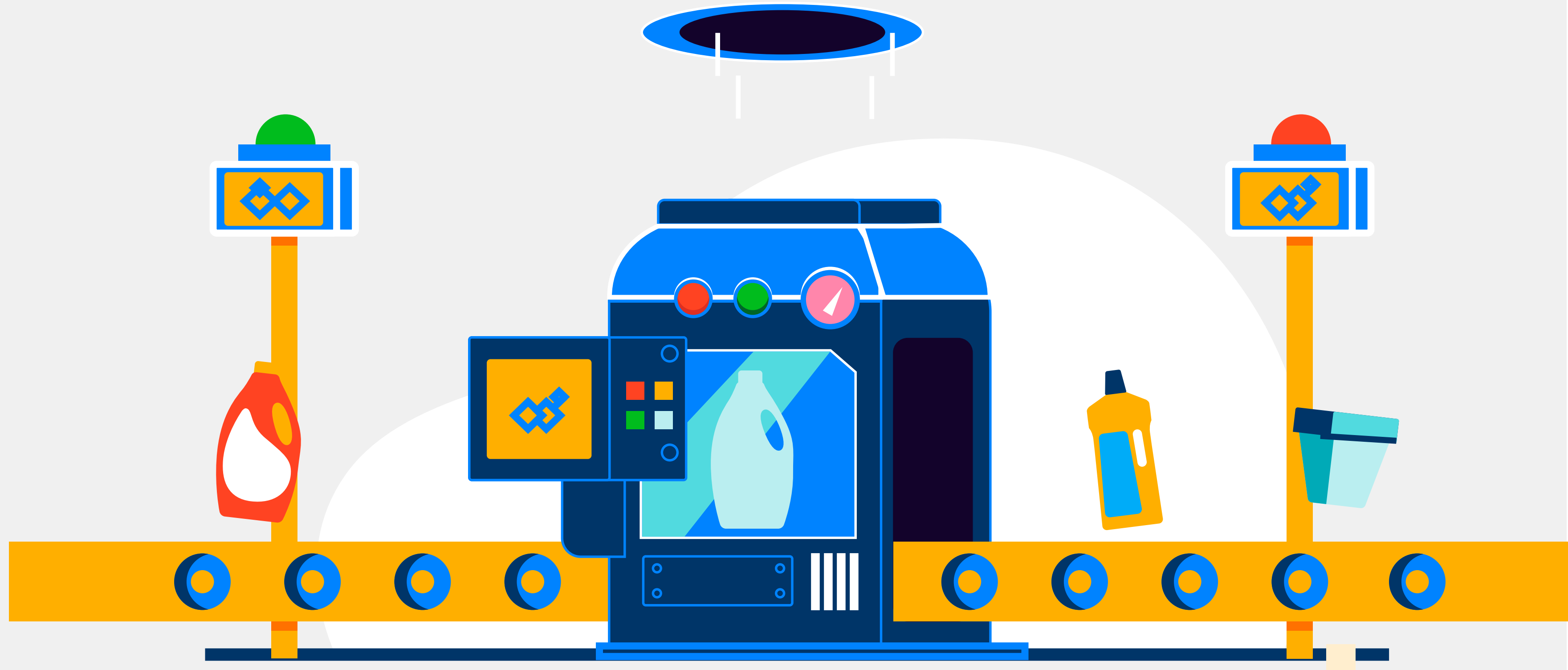

Stakeholder's perspectives and engagement

Pille Ubakivi-Hadachi and Kairit Kall, Tallinn University

Stakeholder engagement was carried out through 28 interviews, several discussions, and 2 webinars. It explored challenges and perspectives on using recycled materials, particularly plastics (RP), in new products. The focus was on industrial manufacturers using recycled components and recyclers, aiming to identify barriers to RP adoption and strategies to overcome them.

1. SUSTAINABLE PRODUCTION INFRASTRUCTURE

RPs are crucial for sustainable production but require strong infrastructure and legislative support. In the home appliance (HA) sector, EU eco-design and waste directives[13] were key, though producers stressed the need for economically feasible regulations. The automotive sector (AM) expressed concerns over rapid regulatory changes, which can overwhelm industries needing time to adapt. Recyclers called for better collaboration with producers, financial incentives for waste sorting, and advances in recycling technologies to strengthen the circular economy.

2. BALANCING ECONOMIC, ENVIRONMENTAL, AND SOCIAL SUSTAINABILITY

HA and AM producers recognized the need to balance economic, environmental, and social sustainability, though these goals often conflict. Strict regulations can increase costs and inefficiencies, such as overlapping reporting requirements. Effective monitoring is needed to address greenwashing and social dumping. Both groups advocated for better waste management, such as improved e-waste tracking and household sorting. Recyclers pushed for product content regulations to enable more efficient recycling (and closing the loop).

[13] REGULATION (EU) 2024/1781 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 June 2024. Establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32024R1781

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3. REGULATORY CONSISTENCY AND INNOVATION

Producers and recyclers emphasized the need for consistent, science-based EU regulations to avoid fragmented local rules. They supported financial incentives for recycled materials and innovation in recycling technologies. Despite challenges from political and economic uncertainties, stakeholders recognized the urgency of transitioning to sustainable production. Collaboration among legislative bodies, waste collectors, recyclers, and manufacturers was seen as essential to creating a circular economy.

4. BARRIERS AND ENABLERS FOR RECYCLED PLASTICS

Barriers to adopting recycled plastics include costly waste collection systems and plastic segregation. The recycling industry faces challenges with mechanical recycling quality and scalability, while chemical recycling can be expensive. Despite these obstacles, HA manufacturers and recyclers are collaborating on innovative recycled materials. The market for recycled plastics remains niche, with insufficient supply to meet the demand. Recyclers see opportunities to enhance recycling technologies but stress the need for better cooperation.

5. INTERNAL ENABLERS AND COLLABORATIVE EFFORTS

Commitment to sustainability, innovation, and dedicated sustainability teams were key enablers for adopting recycled plastics. Collaboration in less price-sensitive markets also supported recycled materials. However, mixed-material designs and safety concerns hinder circularity. All and all, sustainability was seen as a broader concept than just material use, including energy efficiency, emissions reduction, and waste minimization.

6. THE ROLE OF CONSUMERS

Consumer behaviour significantly impacts sustainability, though affordability often outweighs sustainability concerns. While sustainability ranks highly in surveys, it does not always translate into purchases. Producers view consumers as unreliable allies unless regulations or incentives guide the behaviour. Some acknowledged that consumer demand influenced sustainability in the HA and AM sectors. Consumers were seen as rational actors, choosing sustainable products when economically feasible.

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CONCLU- SION

Summary of key findings

The PRIMUS project looked at improving and enhancing the recycling of plastics and their practical application in the automotive sector and home appliances. The consortium was made out of partners in the recycling industry and network, research centres, industry manufacturers, social sciences, traceability and sustainability. This way, the project could benefit from activities including advancing characterisation and decontamination techniques for plastic recycling, recycled plastic integration in industrial part production, supply chain traceability, social acceptance and environmental sustainability assessment.

PRE-1000 was developed to simplify compliance for recyclers by providing a manageable approach to monitoring hazardous substances in recycled plastics, balancing regulatory compliance with practical, economical screening solutions. The tool was validated during the PRIMUS project as an accurate method proving compliance with EU product legislation.

Furthermore, PRIMUS used the full potential of the food contact regulation for recycled plastics by assessing the safety of recycled **HIPS from a refrigerator to be used again in a refrigerator**. The data to write an application was generated, leading to a novel technology process in accordance with Regulation (EU) No 2022/1616.

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CONCLUSION

The PRIMUS project demonstrated how to design full-supply-chain data collection workshops wherein the needs of the recycler are effectively relayed to all other stakeholders in the supply chain, allowing critical information for the recycling stage to be collected over the course of the polymer material's life cycle. The resulting **digital product passport** provides key features for communicating sampling compliance, life cycle inventory data, and material composition.

The developed ex-situ and in-situ **VOC analytics** revealed the main emitted components in the plastic up-conversion line. It was also demonstrated that brominated gaseous compounds can be detected, identified, and even quantified using the inline, in-situ FTIR based gas analyser.

Brominated flame retardants (BFRs) extraction was studied in solvent compositions consisting of mixtures of water, IPA, and NaOH with high debromination efficiency. In addition, the used extraction composition was found to have a large effect on the removal of other plastic additives. Thus, the used solvent composition needs to be tailored according to the targeted application.

Direct mass spectrometric (DIP-MS) was found to be a viable tool for rapidly screening plastic additives from different classes, including antioxidants, plasticizers, light stabilizers, as well as halogenated and phosphorous flame retardants. The most notable advantage and disadvange of DIP-MS is the minimal sample preparation required vs uncertainty related to acquiring quantitative data. This issue was addressed in the PRIMUS project by analysing micro compounded model samples consisting of either HIPS or ABS matrix and a BFR with good correlation between DIP-MS data and XRF analysis. The PRIMUS **quality-quantity match (QQMM)** model was presented as an example of systematic mapping framework to assess the technical, regulatory, and data quality level of plastic recyclates. The application specific technical, regulatory, and data quality levels for recyclates is by nature a complex and interconnected set of information, which complicates design from recycling operations. The presented framework would be beneficial for brand owners and stakeholders in matching recyclate quality level with their intended product specification.

Recycled materials were introduced in different automotive and home appliance parts as part of the PRIMUS demonstrator cases. Primary materials were used together with recycled materials to obtain formulations with different recycled contents. The use of thermoplastic recycled materials is quite common, but the use of recycled rubber materials is much challenging. In this project it was proved that even with rubber we can obtain more sustainable formulations.

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CONCLUSION

A full sustainability framework was developed as part of the PRIMUS Sustainability Methodology involving Life Cycle Assessment (LCA), Social LCA, Circularity, plastic littering risk and System Dynamics. The methodology was applied to the 4 PRIMUS demonstrator cases. Sustainability assessments show general improvements when using recycling content, where impacts like Climate Change always show a decrease in emissions. Only Demo 3 shows a mix between improvements and worse results, mainly due to the large transportation distance of recycled content and intensive energy and nitrogen use in the specific demo recycling process. Furthermore, a higher plastic littering risk is generally seen in the recycled plastic scenarios. However, results would change if a full cradle-to-grave rather than cradle-to-gate analysis was considered, as e.g. landfilling plastic products is considered to have higher plastic littering risk than recycling them.

A wide array of sustainability datasets for recycled polymers, EcoProfiles, were developed. They allow to assess and compare environmental impacts within the industrial average but also to primary production. Hence, decision for recyclates will be backed up from now on with transparent and comprehensive LCA data derived from the PRIMUS project.

Societal perception and engagement was investigated with public surveys in Spain, Germany, Finland and Estonia and a literature review. Findings reveal overall public environmental concern and behavioural commitment to recycled plastics, where drivers to acceptance include the positive perception of safety and environmental friendliness and main concerns relate mainly to health safety, followed by the lack of long-term studies on recycled plastics. Consumers lack sufficient information about plastic recycling, leading to some confusion and distrust.

Final thoughts and recommendations

The environmental benefits of recycling were clearly highlighted while environmental trade-offs like the formation of microplastic, particulate matter or VOCs or quality considerations need further investigation.

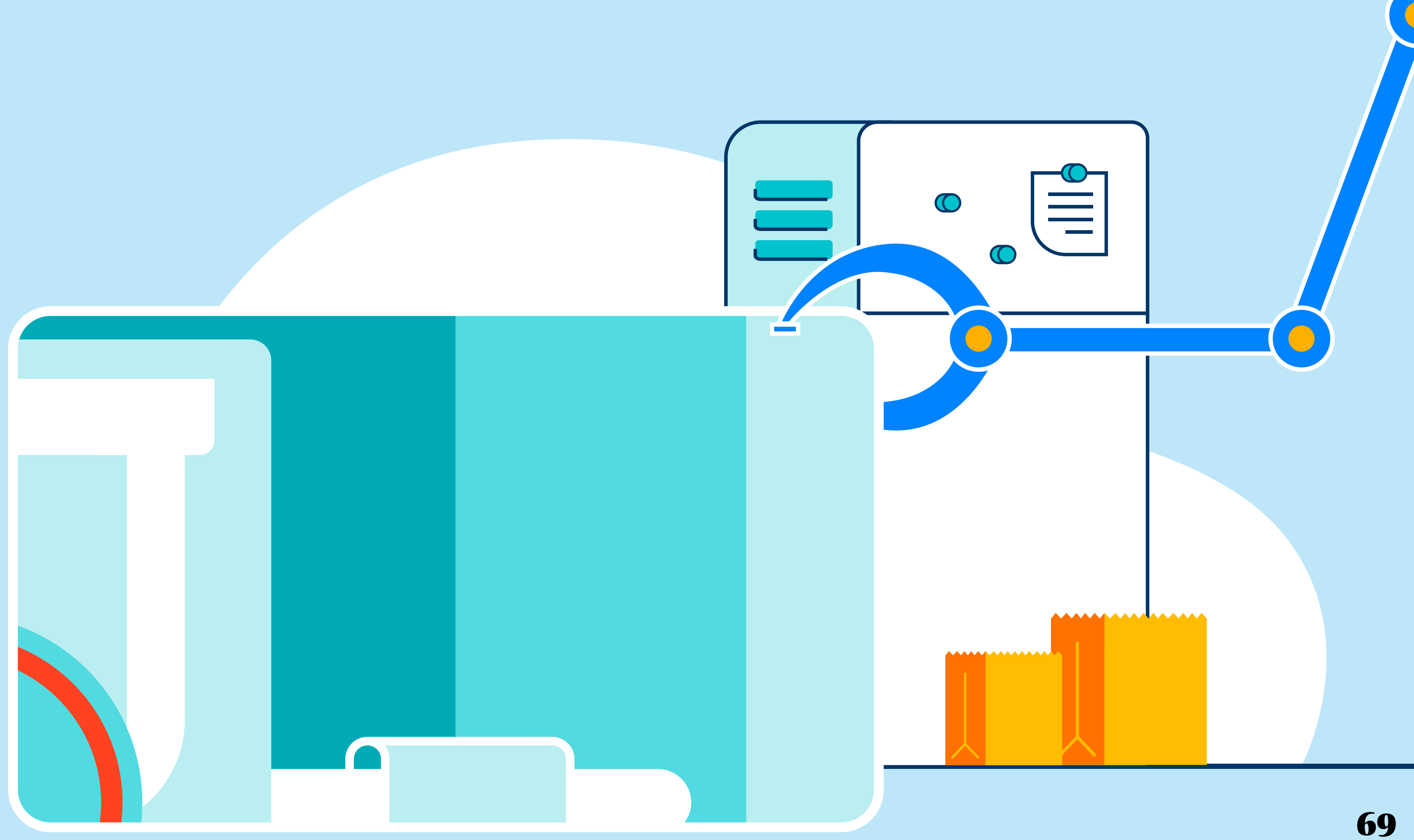
Recyclers should consider adopting PRE-1000 as a standardized tool for ensuring compliance of recycled plastics with the product legislation. By utilizing this tool, recyclers can streamline their monitoring processes, achieving both regulatory compliance and cost-effective screening solutions that help improve operational efficiency.

FINAL THOUGHTS

Further work on the digital product passport is recommended to focus on effective strategies for capturing use-phase data that could aid in the collection and sorting of plastic waste before the recycling stage. Integration of the digital product passport concept with existing operational workflows of polymer compounders and certification bodies would streamline their adoption in industrial settings.

Companies working on advanced recycling processes should explore opportunities to leverage the findings from the PRIMUS project, particularly in assessing the safety of recycled plastics for reuse in specific applications, such as HIPS from refrigerators. This could lead to the development of novel recycling technologies that expand the range of materials eligible for safe use in food-contact applications.

Based on the PRIMUS quality-quantity match model (QQMM) results, it is recommended to classify and report recyclate data with standardised data quality levels (e.g., per prEN ISO 18065) which enables systematic mapping of complex and interconnected data.



Product manufacturers should be accurate and fussy during the selection of the recycled materials. The technology used to produce the final parts needs to be considered to obtain formulations suitable to use in the production line.

Recycled plastic use is a more sustainable option compared to primary plastics. It is recommended that these are sourced locally to avoid big transportation efforts that can counter act sustainability improvements from recycling. Plastic litter risk can seem to be higher on the production of recycled plastics when speaking about cradle-to-gate perspective. We musn't forget that the cause of plastic litter is the production of primary plastics to start with. In a System Dynamics perspective, the supply of recyclates seems to be a struggle, and the increasing amount of plastic production a concern.

Finally, raising awareness about regulations, the plastic lifecycle, innovative recycling technologies, and the ecological impacts of recycled materials is crucial for fostering acceptance and promoting sustainable practices amongst consumers.

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PRIMUS BEST PRACTICE BOOK.

We hope these best practices are helpful for further projects.

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