Sustainable Plastic Packaging from Sorted Municipal Waste and Its Life Cycle Assessment Using Digital Product Passports

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Abstract. Plastic waste from packaging is being repurposed to create new products with similar processing and usage properties as virgin plastics. Understanding its composition, degradation processes, and recycling steps is essential to open up new fields of applications. To shed light on sustainable uses of recycled plastics in packaging, this paper presents interdisciplinary research which investigates and connects three areas to a holistic product view from the material to the end of production. The first area focusses on the exploration of recyclate applications by analysing and processing different recyclates and design-recyclates to identify their potential in plastic packaging products. In the second research area an evaluation model to assess the ecological sustainability of plastic packaging is developed, considering factors like material composition and processing methods. The final area focuses on developing a platform-supported information system for sharing relevant sustainability data, considering mechanisms to enhance data sharing.

The challenges and opportunities of using recyclates in packaging are examined through a demonstrator product—a recyclable stand-up pouch which also contains recyclates. The analysis involves production, life cycle assessment, and utilising platforms for data sharing throughout its life cycle. The paper delves into methods to combine the practical analysis of material behaviour, the mechanisms to use and share the resulting material, machine and process data and the sustainability assessment of this data.

Keywords: Digital product passport · Life cycle assessment · Plastic packaging · Recyclate

1 Introduction

Today, less than 10% of plastics from municipal waste in Europe are mechanically recycled [1]. Reasons for the low mechanical recycling rates are non-recyclability due to improper product designs, an unknown or complex material-composition of such plastic

K. Dröder and T. Vietor (Eds.): CD 2024, Proceedings, pp. 377–392, 2025.
https://doi.org/10.1007/978-3-658-45889-8_29

products and a general lack of a clear and commonly binding definition of "recyclability". Especially packaging plastics are considered difficult to recycle due to their complex multimaterial product composition [2, 3]. Those products are produced almost exclusively from fossil fuels and not from recycled plastics. However, the production of packaging plastics made from municipal waste recyclates faces different challenges along the value chain. Due to the different origins of municipal waste and the numerous grades of plastics, recyclates are subject to material variations and their properties are difficult to predict. This is further complicated by the numerous effects that contaminants can have on recycling and manufacturing as well as product properties. Various methods exist for examining the properties of recycled plastics, but there are no established standard specifications that can be used to conclude the processing and usage properties. Existing standards (e. g. EN 15344 and EN 15345 for PE and PP) for the characterisation of recycled materials are often not sufficient for a comprehensive examination of the material quality, as they contain few general-use test methods [4]. In order to increase the proportion of PCR in plastic packaging and to quantify the impact on the environment compared to packaging made from virgin material, a holistic product analysis is required.

2 State of the Art for an Interdisciplinary Approach to the Ecological Assessment of Plastic Packaging

Regardless of the type of recycling, recyclates must meet the general legal framework conditions, e. g. producer liability and achieving the same required product specifications. The multitude of stresses that recyclates experience during their repeated processing and usage results in an overall higher level of degradation. During processing, the polymers are exposed to strong forces (mostly shear with some extension) and high temperatures, which affect the polymers and lead to thermo-oxidative and shear-induced chain scission, chain branching, or crosslinking of the material [5–8]. The amount of degradation depends on the chemical properties of the polymer and the selected processing conditions. With the specific choice of processing parameters, degradation and thus direct effects on process stability and product quality can be controlled to a certain extent [9–13]. While degradation mechanisms can significantly affect the material properties, this is further influenced by the material composition and other impurities [14, 15]. Such impurities contain e.g. printing ink systems, adhesives, barrier materials, additives (e. g. processing aids, compatibilisers) and fillers (e. g. minerals). Overall, the various components influence the material properties to an unknown extent, depending on their type and concentration. In addition to the direct influence of the impurities on the processing behaviour, they also influence the degradation of polyolefins. For example, metallic impurities or pigments used to colour plastics can accelerate thermo-oxidative degradation [16, 17].

In contrast to the decreasing material and product quality of PCR-products, the sustainability and ecological environmental impact improves compared to products from virgin material. So-called life cycle assessments (LCA) are therefore suitable to evaluate the sustainability of products and processes. In this way, the sustainable performance of a product made from recyclates can be compared with products from virgin material.

Moreover, different manufacturing and recycling processes as well as different usage scenarios of recyclates are considered using defined impact indicators to describe the environmental impact. In a circular economy, an ecologically and economically use of recyclates consequently places requirements on each step of the product life cycle. The European Union is currently investigating the extent to which digitisation in form of product passports and the associated transparency of information on product properties can support the transition to a more resource-efficient internal market [18, 19]. In such a product passport, necessary data regarding the product history of packaging (e. g. net CO_2 emissions) is stored and exchanged between different actors. Provided that such data is collected online, product passports offer enormous potential with regard to the calculation of environmental impacts in life cycle assessments. It is thus possible to make greater use of primary data than of secondary data, i. e. resource consumption and processing conditions measured on production plant machinery. This enables improved transparency for consumers and stakeholders to make more informed decisions by means of LCAs. In order to quantify the environmental impact of product systems, LCAs been carried out since the early 1970s. [20] With the introduction of ISO standard 14040, the first internationally recognised standards for conducting LCAs were implemented [21] whose phases and interaction (cf. Figure 1) are described in detail in ISO 14044 (2006) [22].

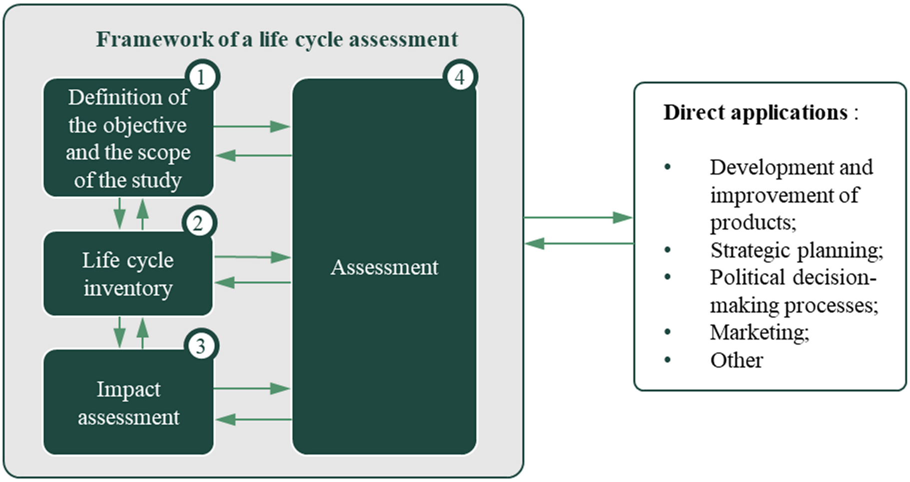

Fig. 1. Phases of a life cycle assessment according to ISO 14040 and ISO 14044 [21, 22]

The LCA method is designed to be applicable to any product or process. Therefore, the method offers the advantage allowing for many degrees of freedom to analyse the desired object, but also makes it difficult to compare different LCAs. The approaches and methods chosen for each LCA lead to different results for the same product system [23]. Only broad assumptions regarding the environmental effects of comparable items can be made.

Digital platforms offer the opportunity to fundamentally improve the comparability of LCAs in the future. They enable pre-competitive exchange along the value chain and they are an important tool for developing and coordinating sustainable products and services. [24]. One challenge for the comprehensive utilisation of LCAs is the lack of data exchange between individual companies to evaluate a product or functional unit beyond the company boundaries. One solution for the corresponding cross-company data exchange are digital platforms on which data can be stored or made accessible, shared and, depending on the application, downloaded. The provision of production, quality, and utilisation data can be used for impact and sustainability analysis. Platforms are characterised by properties like real-time capability, flexibility, geographical independence, and maximum scalability. This is advantageous in terms of network effects, as the benefit of individual participants increases with the number of participants. However, the use of platforms by companies is barely established [25]. Concerns about trust between collaborative partners and data security, sovereignty, and integrity are high. Those challenges are met by GAIA-X as a suitable standard/initiative. GAIA-X is a concept for data-driven ecosystems where the six principles, openness, transparency, interoperability, federation, authenticity and trust, are enforced through technical guidelines. In GAIA-X compliance creates digital sovereignty, independence, and security according to the Data Protection Regulation (GDPR) [26]. The initiative introduces concepts that deal with data storage and cloud connected elements with a focus on sovereign cloud services and cloud infrastructure. Regarding the willingness to share data, the definition of governance structures is important. Governance here refers to a system of decision rights and responsibilities for information-related processes that are executed according to agreed models. [27]. The link between the Gaia-X initiative and the product passport is based on another initiative—Catena-X. This initiative is collaborative, open data ecosystem of trust for the automotive industry in Europe with the goal of increasing resilience, innovation, and revenue opportunities and creating equal access to information flows for all actors along supply chains (e. g. digital carbon footprint or traceability in accordance with the Supply Chain Act) [28]. Its system architecture is based on GAIA-X with e.g. the data sovereignty and security aspects. The value proposition is the first time offer of a sovereign, multi-tier data sharing and use case collaboration across the entire value chain. In Catena-X multiple use cases are examined. In the use case of circular economy the community is working on a product passport. Due to relevancy of a product passport as a use case for data sharing, this example is part of the overall research goal.

As the challenges for ecological plastic packaging encompass various industries and aspects along the value chain, an interdisciplinary approach is necessary. This research provides a possibility to connect the different necessary areas and to generate knowledge about material behaviour as much as data generation, data usage and interpretation in context of product sustainability.

The research objective is the ecological optimisation of plastic packaging using digital technologies. For this purpose, a general description model for evaluating plastic packaging is being created on the basis of a stand-up pouch as a demonstrator product.

3 Methodology and Preliminary Results Using the Example of a Mono-Pe-Pouch

The first strand of research is dealing with the possibilities and limits of using mechanically recycled polyolefins in packaging with the aim of increasing the use of recyclates in the packaging sector. The influence of different material compositions or impurities in combination with the degradation of plastics has not yet been sufficiently investigated and studies with pure virgin material cannot be directly transferred to recyclates. Many analytical methods, as for example differential scanning calorimetry (DSC), infrared spectroscopy (IR), capillary rheometry or gel permeation chromatography (GPC), already try to assess the quality of recycled plastics [29]. Nevertheless, there are still uncertainties about necessary quality parameters, to ensure the recyclate's performance in new applications regarding for example resulting rheological, fatigue and breakage behaviour or processability. According to the researchers, the current non-binding and partially incomplete standards for recyclates and virgin materials lead to plastic packaging manufacturers agreeing individual and bilateral on different quality parameters and delivery conditions. Plastics analysis and testing is a central component in generating new standards. At the same time, it is important to determine the possibilities and limits of various processes such as cast packaging films, blown films and injection moulding and related applications to increase the use of recyclates and thus meet current EU requirements (e. g. Packaging and Packaging Waste Directive, PPWD) [30].

With the aid of a product demonstrator the theoretical product life and the real material and product properties can be correlated. Design for recyclability plays an important role. The more recyclable a packaging is designed, the easier it is to separate the individual plastics by type and feed the waste into the highest possible value stream. As the use of flexible plastics can save packaging material compared to rigid packaging solutions a stand-up pouch for a cleaning agent with a spout is chosen as a demonstrator product [31]. The stand-up pouches currently available on the market are fully recyclable, but contain little or no post-consumer recyclate (PCR). Therefore, a complex mono-material structure with a high proportion of recyclate was developed (100% recyclate in the spout and $> 60\%$ recyclate in the film laminate). As no fractions or recyclates from flexible PP waste are currently available on the market, the bag is made exclusively from PE [32]. Figure 2 shows a schematic representation of the pouch and the corresponding laminate structure of the film consisting of a blown PE film, a laminating adhesive, printing ink and a biaxial oriented PE film. Furthermore, the challenges in the production of the packaging components are presented.

3.1 Challenges During Processing of Recyclates

In a first step, commercially available recyclates were processed and analysed to assess the extent to which the various materials differ and are suitable for the respective production processes. For this purpose, PCRs from different providers (e. g. Vogt-Plastic GmbH, Der Grüne Punkt Holding GmbH & Co. KG, Ecoplast Kunststoffrecycling GmbH, Interzero Holding GmbH & Co. KG, Morssinkhof-Rymoplast) were analysed. The purity of such recyclates compared to virgin materials is relatively low, making them the greatest challenge for processing. Figure 3 shows an example of a blown film made

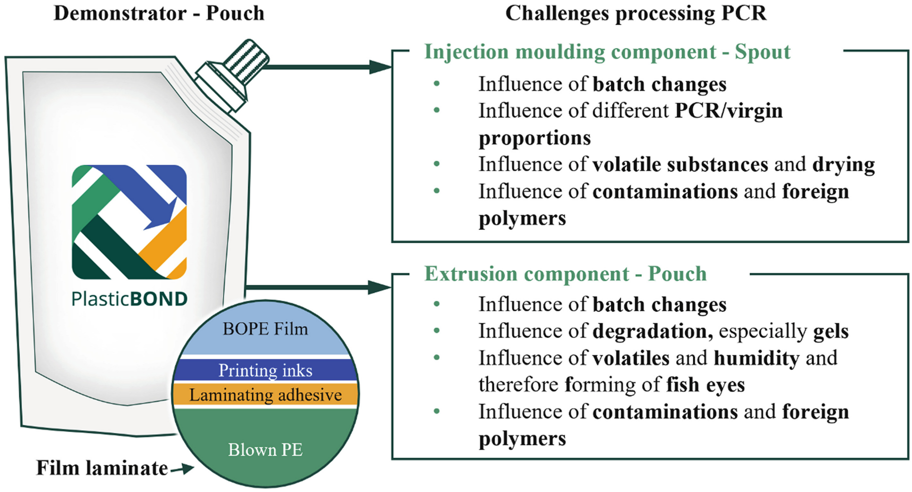

Fig. 2. Design of the demonstrator pouch including the challenges of processing PCR.

from mechanically recycled PCR with a possible composition based on the material analyses conducted.

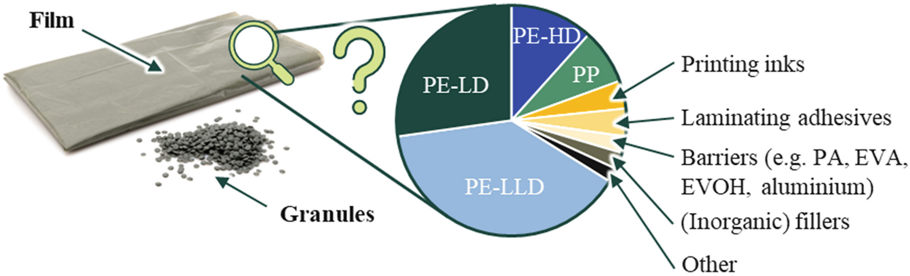

Fig. 3. Exemplary composition of a film recyclate

To investigate the influence of impurities and material degradation on the processability, recyclates and so-called design recyclates (contaminated virgin materials [33]) were repeatedly processed in blown film and regranulated afterwards. Various PEs from SABIC, Riyadh, Saudi Arabia, were used for this purpose. The impurities used included an impact-resistant polypropylene (PP) copolymer for film applications, an ethylene-vinyl alcohol copolymer (EVOH) with an ethylene content of 32 mol%, a PE-based compatibiliser grafted with maleic anhydride (MAH) for physical bonding to the PE phase and chemical bonding to polar phases (PA or EVOH), binders and a calcium carbonate as a filler. The gained knowledge enables to select and develop simple methods for determining and improving mechanically recycled PCR quality (e.g. adapting existing design guidelines). Furthermore, the prediction of processing options depending on the PCR quality is targeted. In the long term, this should enable the creation of a material and process specification to assess the quality of recycled materials, e.g. in the form of digital product passports (Research strand 3).

The first pouch component, the film laminate, consists of a biaxially stretched top film and a blown film for sealing. Both the top film and the blown film consist of three layers: a relatively thick layer of recycled material ($> 70\%$) surrounded by two thin outer layers of virgin material. The outer layers of virgin material improve the processability, sealing properties and odour formation during and after processing. One of the most critical challenges during film extrusion of mechanically recycled PCR is the amount of high volatile components and moisture in the material. While virgin PE generally does not absorb moisture, this does not appear to be the case with PE recyclates due to impurities (e. g. ethylene vinyl alcohol (EVOH)). During processing, this leads to fish eyes, i. e. holes in the film, and thus to rejects. Pre-drying can provide a solution, but only to a limited extent. Furthermore, lower processing temperatures e. g. 180 °C in PE film extrusion lead to fewer or no fish eyes. At higher temperatures (e. g. 230 °C), on the other hand, the proportion of fish eyes increases and film breaks occur. In addition, large differences were found between PCRs from different recyclers (e. g. Vogt-Plastic GmbH, Der Grüne Punkt Holding GmbH & Co. KG, Ecoplast Kunststoffrecycling GmbH). It is therefore assumed that a higher processing temperature during recycling leads to increased degassing and therefore fewer volatile components escape in subsequent processing steps. Another major challenge in film extrusion and the further processing of the films into a laminate are so-called gels. Gels are any small defects that change a film product (e.g. cross-linked material, highly oxidised material, filler agglomerates, fibres, remelted polymer) [34, 35]. Microscopic investigations have shown that a large proportion of the gels in mechanically recycled materials consist of cross-linked or high-molecular structures [36]. Investigations on design recyclates also showed that the recycling process and the amount of recycling steps influences the size and number of gels depending on the material composition of the recyclates [33]. In addition to impurities such as polypropylene (PP) and EVOH, the use of a MAH-based compatibiliser in particular catalyse gel formation. High fluctuations were also observed with regard to the PP content in commercially available recyclates. For example, the PP content in film recyclates ranged from $< 1\%$ to greater than 15%, which in turn influences gel formation. The mechanical properties, on the other hand, are less influenced by the mechanical recycling process. Only a slight decrease in the tensile strength of the mixtures as well as the maximum elongation after recycling was detected. No influences on the impact strength were observed [33].

In addition to the properties of the extruded packaging film, the production of the spout by injection moulding is considered and analysed. The spout needs to fulfil various quality requirements. On the one hand, the part must have sufficient rigidity, strength and precision concerning the rotating mechanism and, on the other hand, it must have a high level of geometric accuracy for a reproducible sealing process between the spout and the film pouch. During the injection moulding trials different aspects of the material-process interaction are analysed. The influence of the set parameters (e.g. injection speed, holding pressure, mould temperature etc.) is just one example, but due to the differences in the material composition also other effects like the influence of volatile substances, batch changes and material conditioning (e. g. drying) are considered. First trials of two materials show that the PCRs show similar reactions to changes in process settings as virgin material. For example an increase in melt temperature (+ 10%) and an increase in injection speed (+ 60%) tend to decrease the strength (- 3%). Furthermore, the conditioning of the PCR influences the mechanical behaviour significantly. Drying, even though recommended by the recycler, can lead to further ageing of the material which is detectable during processing (slight increase in injection pressure) and results in brittle behaviour during mechanical testing. The results of the injection moulding processing of the recyclates show a strong influence of the material composition and the resulting varying processability on the process stability and part quality. Indicators such as the viscosity and the part weight can be used to monitor reproducibility, but analysis of the correlation between machine data, viscosity, part weight and part strength suggest that similar processes can still result in considerably different part qualities. A product passport in which the material history and composition is documented is therefore useful for estimating the resulting component quality depending on the material and process control.

3.2 Assessment Model for the Ecological Sustainability of Packaging

The second research strand focuses on LCA. In addition to the identification and characterisation of all relevant material and energy flows a general description model for the evaluation of plastic packaging is developed. The focus of LCA is always on comparability between potential alternatives, such as the comparison of sustainability between linear recycling and closed-loop recycling of packaging. The models and methods established are then validated using the demonstrator product. An increase in the recycling rate does not necessarily mean an increase in resource efficiency. With the determination of the product design, the processes for manufacturing and further processing of the products as well as their recycling, the energy and material requirements of a production are predetermined. Additionally, transport routes also influence the environmental impact. To estimate the environmental impact, the multitude of energy and material flows of the individual process steps of a product system must be combined into an overall balance. These balances are analysed for their environmental impacts such as greenhouse gas emissions or human toxicity. This is done in LCA [21]. Emissions from greenhouse gases are described by CO_2 equivalents as an indicator of the impact on global warming [22]. The calculation of environmental impacts such as eutrophication requires the use of characterisation models based on emitted energy and material flows [21].

With the preliminary studies from [37], a model was developed with which the main environmental impacts of a packaging pouch along its life cycle can be assessed with the help of an LCA. The model can be used to evaluate different end-of-life scenarios depending on the scope of the study (cradle-to-gate, cradle-to-grave, cradle-to-cradle). The product system and the specified process modules for a pouch's life cycle are shown in Fig. 4.

The four stages of the life cycle: raw materials, production, usage, and end of life, are represented by the product system. Some manufacturing procedures that are part of the pouch's value chain are also applicable to the majority of other plastic products. All pouch components are made using different production processes from mechanically recycled plastic and partly from virgin plastic. When evaluating the packaging only the

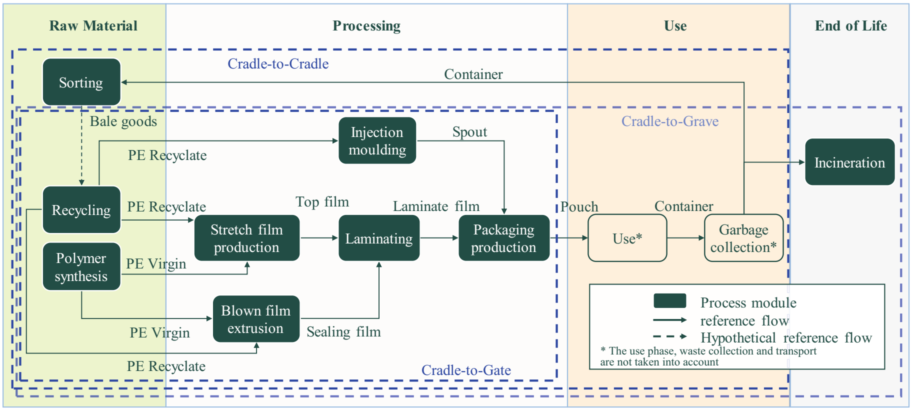

Fig. 4. Product system of pouch manufacturing

manufacturing itself is considered, parts of the use phase for example the content of the packaging are discarded.

In a preliminary study, an LCA was conducted for a pouch to identify the relative influence of the individual production steps [37]. For this purpose, additional modules such as transportation or pre-drying of the granulate were considered. The reference flow considered for the LCA corresponds to the production of a stand-up pouch. For the LCA the open Source Software OpenLCA was used. [38] The environmental impacts were calculated with the ReCiPe Method. [39] The used LCI are from ecoinvent 3.9. [40] This preliminary study endeavors to delve into the intricate landscape of individual process modules within the framework of Life Cycle Assessment (LCA). Life Cycle Assessment, a widely utilised methodology for evaluating the environmental impacts of products and processes, involves various interconnected components. However, a detailed understanding of the distinct process modules is imperative for a comprehensive analysis. The primary aim of this study is to acquire nuanced insights into these individual modules, setting the stage for a more profound comprehension of the broader LCA methodology. The results of the different environmental impacts can be seen in Table 1.

The largest share of greenhouse gas emissions is attributable to the extraction and provision of raw materials. Nevertheless, the production of the pouch has a non-negligible share of greenhouse gas emissions. Based on this study, the next step is to specify the modelling of raw material production and manufacturing to derive the potential for the circular economy [37]. The next step is to enrich the developed model with primary data of the pouch production.

3.3 Design of a Platform for Sharing Material Data

The third research strand focuses on the information and data flow-related aspects of LCA and the design of a platform for sharing data while maintaining security, sovereignty, and integrity aspects according to GAIA-X. In this case, a platform should primarily enable data-driven LCA as well as information-based cooperation between the players in the plastics processing value chain. The first task is to identify all data flows and characterise

Table 1. Relative results of a preliminary LCA study for a stand-up pouch [36].

Impact Category	Unit	Process modules [%]									
		Raw material	Pre drying	Film-extrusion	Spout	Post process	Refine-ment	Filling	Transport	Incinera-tion	Landfill
Global Warming	kg CO_2-eq	70.8	1.0	7.3	3.1	4.5	4.5	4.5	0.9	2.9	0.4
Acid[1] Soil	kg SO_2-eq	69.9	0.7	8.6	3.5	3.7	3.7	3.7	2.0	3.1	0.9
Eutro[2] Freshwater	kg P-eq	83.6	0.1	0.9	0.4	0.6	0.6	0.6	0.3	1.0	11.9
Eutro[2] sea	kg N-eq	69.7	0.8	7.5	2.7	3.5	3.5	3.5	3.7	4.2	1.0
Particulate Matter (PM2.5)	Illnes-rate	62.5	0.9	11.9	4.5	4.0	4.0	4.0	1.4	5.8	1.2
Water use	m^3-eq	45.7	1.2	9.1	4.0	5.0	5.0	5.0	0.3	24.3	0.3

Legend: [1]Acidification, [2]Eutrophication them in terms of collection type, storage location, and format. This is important for defining process interfaces. The challenge in the context of the PlasticBond research project lies in dealing with new technologies for storing, managing and orchestrating manufacturing process data for which there is still no sound empirical evidence. While maintaining compatibility with established standards, solutions and norms, secure data exchange is to be ensured. This requires the definition of all desired functionalities of such a marketplace and their continuous completion. When determining the requirements for a platform, the first step is to define feature classes to make the individual requirements clearer and more transparent. Requirements for a data marketplace were derived with the help of analyses of scientific literature, expert discussions and methods of error analysis of technical systems such as FMEA. For structuring reasons, these were divided into 14 feature classes (cf. Figure 5). Each of these feature classes contains at least one feature that can be fulfilled in different solution specifications.

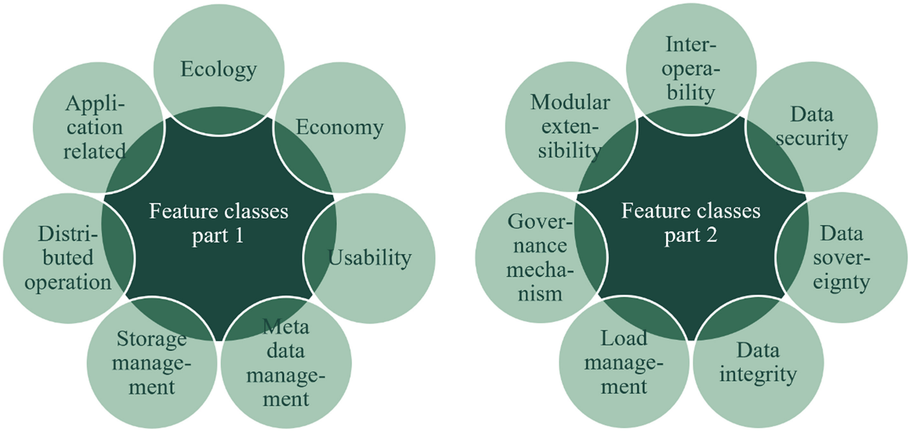

Fig. 5. Categories of the specification sheet for requirements of data marketplaces

All the requirements of potential stakeholders for the platform to be used are defined in a specification sheet. This ensures a certain scalability. Based on the determined requirements of the stakeholders, such as data providers and data users, the requirement specification follows on the part of the platform developer including technology recommendations for the implementation of specific customer requirements, for example, security and compliance demands. Based on these specifications, the platform developer offers a functional specification in which all (safety) technical and infrastructural features are prepared in relation to the customer's requirements. Without harmonisation of the requirements with the solution approaches, customers will lack the necessary acceptance and (intuitive) understanding to join the platform and share their data.

Following, each actor uploads the material and energy flow data required for LCA into the platform while maintaining data sovereignty. A mathematical model makes use of the LCA data identified and calculates the environmental footprint of each process step and/or the entire value chain. Results can be viewed by others upon request and, if necessary, against payment. The element of potential payment for access to data leads to the final aspect of the third research strand: New business models are identified and developed for the plastics processing value chain and their potential is demonstrated.

The main objective of the ecological optimisation of plastic packaging is to provide a wide range of options for exchanging information as a basis for calculating a life cycle assessment. The focus is on the provision and exchange of primary data for maximum accuracy of the results as well as increased flexibility and transparency regarding the development of the calculation logic. Aggregated data or theoretical values reduce these factors and may involve greater effort. In addition to the calculation logic to be developed, the configuration of the platform poses a major challenge. It is subject to three central requirement categories to counteract the current scepticism of companies in data sharing. Data sovereignty, integrity and security must be guaranteed for network participants. This means that data is recorded transparently and stored in a trustworthy manner, whereby data sovereignty always remains with the owner and ownership is not transferred to centralised bodies or third parties (data governance) [41]. In addition, data formats and their content must be homogenised, and correspondingly flexible interfaces defined. This enables the integration of many physical assets and existing systems without major additional effort in data acquisition [42]. Furthermore, governance and incentivisation mechanisms must be developed and established to motivate participants in the platform's collaboration network to provide authentic data within the network [43].

The prototype of the data sharing platform was implemented using an existing product from senseering GmbH, which had already integrated the identified core requirements and was therefore able to focus on the development of missing functionalities. The prototype is a distributed platform consisting of various nodes. Each node is owned by a user of the platform. They act as data storage and enable the management and monitoring of connected data sources. A NoSQL database is used to store the data for greater flexibility. An SQL database is used to manage the corresponding metadata. To ensure data integrity, hash values are generated for each incoming data record and stored in a distributed ledger. Due to the security against manipulation, these hash values can be used to maintain the integrity of the data. Scripts between the data source and node consume a data stream and forward it to a node via HTTPS. All nodes are linked via a central marketplace, which manages routing information, controls access control and can be used as an authentication instance, for client management and data exchange. The prototype developed enables companies to store data in dedicated rooms and share it with other parties as required. Individual interfaces to the data storage locations were designed to connect the project partners.

The LCA analyses are to be automated via a separate application on the digital platform. This necessitates the establishment of a standardised data format. The process involves the comprehensive integration of data collection across various stages of value creation. It further requires the development of a sophisticated data model that delineates distinct value creation steps. This model should facilitate individualised data mapping for each company, carefully considering data availability. Crucially, it avoids the granularity of breaking down data per machine or company. In the project, an LCA-orientated ontology was developed for this purpose, which acts as a source map for obtaining information for each process step.

4 Conclusions

In conclusion, the challenges surrounding the ecological optimisation of plastic packaging are multifaceted and demand a comprehensive interdisciplinary approach. Current recycling rates remain low in Europe, primarily due to factors such as improper product designs hindering recyclability and a lack of clear definitions for "recyclability." Packaging plastics, particularly, pose challenges due to their complex composition and reliance on fossil fuels. Mechanically recycled plastics face various challenges along the value chain, including material variations, degradation during processing, and the influence of impurities. Standards for assessing recycled materials are insufficient, leading to individual agreements between manufacturers and a lack of comprehensive quality parameters. The presented research shows opportunities for advanced analysis and evaluation of the material itself and the resulting processing data.

Despite the shown challenges, life cycle assessments (LCAs) are crucial for evaluating the sustainability of packaging solutions. LCAs enable comparisons between products made from virgin materials and recyclates, considering factors such as production, usage, and end-of-life scenarios. The evaluation of the demonstrator shows the positive effects of recyclates and recyclability on the sustainability of a product.

To further allow and improve LCAs, enhanced transparency and data exchange is necessary. Therefore initiatives like GAIA-X, which are presented in this paper, need to be understood, used and enforced to enhance transparency and data sovereignty.

Acknowledgements. The investigations set out in this report received financial support from the German Bundesministerium für Bildung und Forschung (No. 02J20E540), to whom we extend our thanks. We would like to thank our consortium partners Brückner Maschinenbau GmbH & Co. KG, Henkel AG & Co. KGaA, Reifenhäuser Blown Film GmbH, Interzero Circular Solutions Germany GmbH, Arburg GmbH + Co. KG, Pöppelmann GmbH & Co. KG Kunststoff-Werkzeugbau, Carbon Minds GmbH and Reifenhäuser GmbH & Co. KG Maschinenfabrik for the excellent cooperation.

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