Application of Life Cycle Assessment for more Sustainable Plastic Packaging - Challenges and Opportunities

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Abstract. The European plastics industry is in transition to meet its 2050 net zero and circularity targets. In 2020, the overall European recycling rate for post-consumer plastics packaging reached 46%. The European Union set a target for recycling 50% of plastic packaging by 2025 and 55% by 2030. These targets can only be achieved by increasing the use of recycled materials in packaging. Therefore, it is required to design new plastic packaging products, production processes and recycling processes with a focus on easy recyclability and reduced environmental footprint. This publication points out possible benefits, opportunities and challenges of using the well-known Life Cycle Assessment (LCA) methodology for plastic packaging products. First steps towards the development of reduced LCA-based models, which can be used to support the development of plastic packaging products, are presented. One example is a generic recycling process model, which can be used for different packaging materials and provides the basis for further analysis. Another example is the development of an assessment template for current plastic recycling processes. The publication concludes with the identification of open research questions.

Keywords: Plastic Packaging · Life Cycle Assessment · Plastic Recycling.

1 Introduction

The legislative requirements for plastic recycling in the European Union are currently undergoing serious changes. According to Directive (*EU*) 2018/852 of the European Parliament, which is the centerpiece of EU legislation on packaging and packaging waste, until end of the year 2025 a minimum of 50 % by weight of all plastic packaging waste must be recycled. Until end of 2030 a recycling rate of 55% is required by law [1]. This goal shall be achieved, among other actions, through a higher share of recycled material in packaging material production.

The plastics industry is therefore challenged to develop new products and production processes as well as optimized recycling technologies. To increase the share of recycled material in packaging, on the one hand, the recyclate must be of sufficient quality. On the other hand new product packaging must be designed in a way that recyclate can be used for its production and that these new products can be recycled efficiently themselves. This means that topics like "Design for Recycling" and "Design from Recycling" [2] will become more important in the design process of new packaging materials. To evaluate if a new product design is advantageous regarding sustainability over the previous design, the whole product lifecycle has to be considered. This includes manufacturing, use phase and the end-of-life phase. The assessment should be done at an early stage of the product development, because then changes of the product design are still possible at low costs. A possible methodology for the assessment of environmental impacts over their entire life cycle it the well known life cycle assessment methodology (LCA). In this work, possible benefits and challenges of an early LCA of plastic packaging are identified and first steps towards an comprehensive modified LCA approach for plastic packaging are presented. It therefore provides initial answers on the overarching research question of how plastic recycling can become more environmentally friendly and how LCA can support this.

2 Background Information

This section provides an overview of related topics and gives background information which helps to understand the intended field of application of the later presented methods and tools.

2.1 Plastic Packaging

Plastic packaging plays an important role in protecting, preserving, storing and transporting goods. Different materials and compounds can be used to realize an optimal packaging. In 2021, 39.1% of European plastics demand was destined for packaging materials and over 50% of all European goods are packaged in plastics. Main materials which are used for packaging are polyetylene (PE-LD, PE-HD), polypropylene (PP), polystyrol (PS) and polyethylene terephthalate (PET) [3]. Multi-layer film packaging, which is often used for food packaging to enhance the shelf life of the products, consists of two or more materials with different properties combined in a single layered structure. This provides huge challenges for the recycling process [4]. The current linear value chain for plastic packaging has to be transformed to a circular value chain. Several attempts for this transition can be found in literature. In [5], a way to support the creation of circular value chains through the implementation of an information sharing system is proposed.

2.2 Plastic Recycling Methods

There are different ways to recycle plastic waste. Currently the most common approach of plastic recycling is mechanical recycling. Alternative approaches like chemical recycling, dissolution recycling and organic recycling are also available.
Mechanical recycling is simple, inexpensive and has a low demand on energy and resources compared to chemical recycling. For mechanical recycling, the plastic waste is processed into secondary raw material without significantly changing the material's chemical structure. Most types of thermoplastics can be mechanically recycled with little or no impact on quality.
Chemical recycling is an umbrella term for a set of technologies (pyrolysis, gasification, hydro-cracking, depolymerisation) that change the chemical structure of plastic waste. Chemical, thermal, or catalytic processes break long hydrocarbon chains of plastics into shorter fractions or monomers. These shorter molecules can than be used as feedstock for chemical reactions to produce new recycled plastics.
Dissolution recycling is a purification process. A selected polymer in the plastic waste is selectively dissolved in a solvent. So it can be separated from the waste and recovered in a pure form without changing its chemical structure.
Organic recycling is a controlled microbiological treatment of biodegradable plastics waste under aerobic conditions (composting) or anaerobic conditions (biogasification). It applies to specific polymers and does not produce plastic material, which can be directly reprocessed [6].

2.3 Life Cycle Assessment (LCA)

The LCA methodology is standardized in its basics with ISO 14040 [7] and in detail with ISO 14044. According to ISO 14040, LCA deals with the environmental aspects and potential impact of the whole product lifecycle. This includes the raw material acquisition, production processes, product use phase and the end-of-life. The general environmental impact assessment requires the consideration of resource use, human health, and ecological consequences. In ISO 14044 the LCA methodology is divided into 4 different phases: goal and scope definition, inventory analysis, impact assessment and interpretation.

3 Benefits of LCA in Plastic Packaging

The well known LCA methodology can be used in different stages of the plastic packaging lifecycle to reduce the ecological footprint. On the one hand, it can be used in the design process of new plastic packaging to reduce the environmental impact over the entire lifecycle. LCA results can support design decisions and can also lead to a better recycability of the product at its end-of-life stage. On the other hand LCA can also be used to analyze existing recycling processes, to identify emission hot-spots and to optimize the process steps.

The LCA methodology can be used in the development process of new packaging designs to quantify the influence of design decisions on the environmental footprint. For the comparison of different packaging designs, the whole lifecycle has to be considered. This includes the production of the packaging material, the transport emissions in the use phase and the end-of-life phase which contains the recycling process emissions. Early available LCA results can help to select the packaging design with the lowest environmental impacts. Environmental hot-spots can be identified and possibly avoided. Either through adopted material selection, optimized product geometry or through changes of the manufacturing processes and manufacturing technology. Design decisions often have contrary impacts on the different lifecycle phases. For example, material and weight reduction by use of composite materials can have a positive effect on the raw material and transport emissions, but can have negative impacts on the recycability in the end-of-life phase. Another example is shelf life of food products. The use of multi layer foils in food packaging can increase the shelf life of food products and reduce food waste. Depending on the food product, this can significantly reduce the environmental footprint. But multi layer foils are difficult to recycle. Therefore developers need reliable information as basis for design decisions and the whole product lifecycle has to be considered to find an optimal solution.

LCA results can also be beneficial for the optimization of existing recycling processes and recyclate quality. A possible benefit is the identification of environmental hot-spots in the recycling process. The LCA methodology is capable of analyzing different kinds of environmental impacts such as the carbon footprint, water use, particle emissions and other emissions. Process steps with high emissions can be identified and optimized. Furthermore different recycling technologies can be compared and an optimized recycling process chain can be implemented. This leads to reduced emissions and better quality of the recyclates.

4 Challenges and Solutions for LCA in Plastic Packaging

There are several challenges for the optimization of the plastic packaging lifecycle and for the use of LCA as supportive methodology. In this work, three challenges and their solution, which support the application of LCA in plastic packaging recycling, are presented. The integration of the discussed methods and tools is shown in Fig.1. In order to optimize the environmental footprint of the whole plastic packaging lifecycle, as a first step, the current situation must be analyzed. Therefore a standardized assessment template for the recycling process of different polymers can be helpful. Further, a generic recycling process model is required to speed up the modeling process for LCA. It should be possible to tailor this generic model to a detailed recycling process model of all common plastic packaging materials. Finally an in-dept analysis of hot-spot recycling process steps must be performed to gain knowledge on how these processes can be optimized. As a first step, energy intensive process steps like the extrusion process are analyzed in detail. In this section, possible solutions to overcome the mentioned challenges are presented.

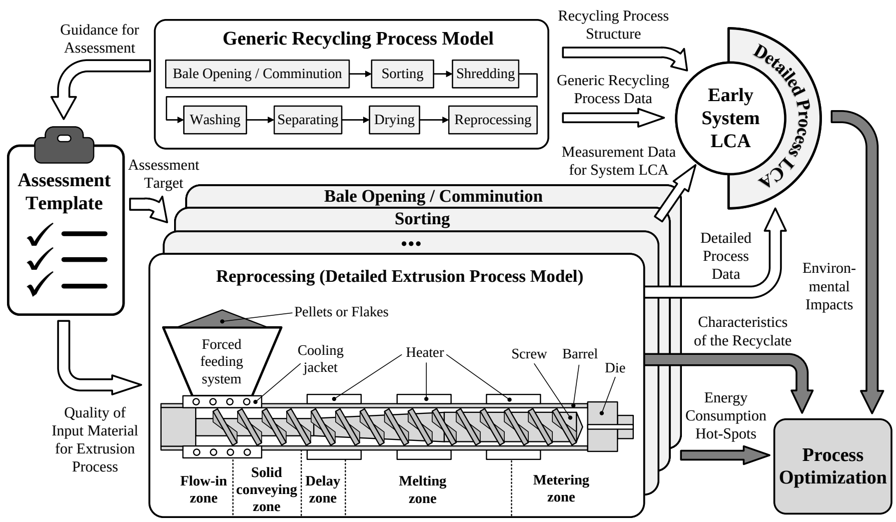

Fig. 1. Integration of the proposed models and tools.

4.1 Assessment Template for Existing Recycling Processes

In order to calculate the environmental impacts of an existing plastic recycling process, comprehensive information and process data is required. For the collection of the required data, an assessment template was developed. It supports the assessment of energy and material inputs, recycling process setup and recyclate quality and ensures that all relevant information is considered. The challenge was to identify relevant indicators from the literature, which are characteristic for plastic recycling process emissions and recyclate quality. A comprehensive literature study, considering publications of European environmental agencies [8], [9], scientific books [10] and European standards for plastic recycling (EN 15342:2008 to EN 15348:2014), revealed a variety of relevant indicators. Based on this identified indicators, an assessment template was set up and structured in Microsoft Excel. For a better overview, all indicators were assigned to one of the three main categories which are preparation for recycling, recycling processes and secondary material. In the first two segments of the template, system in- and outputs are described while the third segment is used to evaluate the quality of the recyclate obtained. The main categories of indicators used for the assessment template are:

1. **Preparation for recycling**
   (a) Method of gathering
   (b) Transportation (mode, distance,...)
   (c) Inputs of sorting and cleaning systems (electricity, water,...)
2. **Recycling processes**
   (a) Inputs of recycling processes (electricity, water...)

   (b) Emission of greenhouse gases (CO_2, CH_4,...)
   (c) Additives (light stabilizers, plasticizers,...)
   (d) Output per day (tons)
3. **Characteristics of secondary material**
   (a) Optical (color, transparency,...)
   (b) Mechanical (density, elasticity, grain size,...)
   (c) Thermal (softening temperature, mass reduction,...)
   (d) Chemical (alkalinity, residual moisture,...)
   (e) Rheological (melt flow rate, dry flow rate, intrinsic viscosity,...)

The developed assessment template ensures that all relevant data for the LCA of recycling processes is collected and documented in a standardized way. This data can then be used for the calculation of the environmental impacts. The template is responsive regarding the type of material and expandable in all its categories and single indicators. Further work to implement LCA calculations based on the inserted data directly in the assessment template is required. Furthermore, different use cases will be assessed with the template to test its applicability. Based on best- or worst-case examples, assessment score-ranges for more or less effective recycling processes should also be identified in the subsequent research progress.

4.2 Generic Recycling Process Model

For the mechanical recycling process of plastic packaging, a sequence of different processes steps is required. Seven main steps, which are described below, have to be considered for mechanical plastic packaging recycling. To speed up the LCA of the whole plastic recycling process and to ensure that no process step is missed, a generic model of the recycling process is helpful.

1. **Bale Opening / Comminuting** - The plastic waste is delivered to the recycling facility in form of bales, which must be opened and shredded before further processing can take place. Therefore, commonly a single shaft shredder is used. [11]
2. **Sorting** - The collected plastic waste consists of a variation of different plastic types and other materials, such as metal or wood. It is sorted using different technologies to achieve the highest possible purity of the recyclate. [12] There are different types of sorting technologies that can be used in different combinations. In a first step, non-plastic impurities in the waste stream are typically removed by manual sorting. Waste screens and drum separators segregate materials based on their size. Air separators and ballistic separators can than be used to remove light materials like plastic films or paper. Magnetic separators and eddy current separators remove metal objects. Different types of plastic can be identified by use of near infrared sensors (NIR) and the separation is then obtained by a strong jet of air.[11]
3. **Shredding** - In this step, the size of the plastic parts is reduced. Through the reduced volume, in the following process steps, a larger amount of plastic can be processed at the same time and the density of the material is increased.[12]

4. **Washing** - The washing of the shredded plastic waste is a step which is not always required for all sorts of plastics. Sometimes the plastic flakes are processed directly after shredding without washing.[12] There are different ways to clean the plastic flakes. Friction washers, where the cleaning process is based on intensive mechanical friction, are used to remove glued-on labels. In dry friction cleaners, impurities are removed by friction without water through high concentration of material in rapidly rotating throwing blades and separated by a surrounding screen basket.[11]
5. **Separating** - A further separation takes place to remove as many impurities as possible. This separation is applied to protect the subsequent machines from damage and to separate different polymers. Sink–float separation is often used in plastic recycling processes. For this process, water is used as separation liquid. Some polymers, such as PET, PVC and PS, sink to the bottom and others, such as PE, PP and EPS, float on the surface.[11] So a separation of different polymer types can be achieved.
6. **Drying** - After the separation a drying process is conducted. This process can be very energy intensive. The washed particles are dried to a certain moisture level, which is about 0.1 percent by mass.[12]
7. **Reprocessing** - After washing, the plastic flakes are reprocessed. Cutting mills can be used to produce fine plastic flakes which can than be used as raw material for the subsequent extrusion process.

Based on the above-mentioned recycling steps, a generic model of the whole recycling process, including average values for energy, water and additive consumption of each process step, was developed. This generic model contains relevant information which is required for the LCA of different plastic packaging recycling processes. The aim of such a generic recycling process model is to speed up the modeling process for LCA and to ensure that no process step is missed.

4.3 Detailed Extrusion Process Model

The extrusion process is an important part of the recycling process of plastic packaging. It is an energy-intensive process that has influence on the quality of the recycled material. Therefore it is worth to have a closer look on this recycling process step. Most often, single screw extruders are used for recycling, as they are very reliable and offer a great price-performance ratio [13]. When the polymeric material has entered the single screw extruder, the material is conveyed, compressed, heated, melted, pumped, and homogenized. Additional degassing or mixing steps are possible. After the material has left the extruder, it is filtered and later the material is cooled and granulated. Models of the process are needed to optimize the quality of the recycled material and to minimize environmental impact by reducing wear and optimizing energy efficiency. To model the function of a single-screw extruder, the process is divided into several functional zones which are displayed in Fig.1. The material enters the extruder in the flow-in zone. Forced feeding systems are usually used in recycling processes. In the solids conveying zone, the material is conveyed, compacted, and compressed. Here the tribological conditions strongly influence the behavior. To achieve good solids conveying behavior, the friction between the polymer and the barrel should be high, and the friction between the polymer and the screw should be low. The internal and external coefficient of friction are important parameters for the description of this zone [14, 15]. In the delay zone, the material then starts to melt. But the biggest proportion is melted at the barrel in the melting zone where specific melting mechanisms can be observed. The screw design has significant impact on the melting behavior in the extruder and on the throughput. When the material is completely melted, the melting zone ends and the metering zone begins. Here the melt is conveyed and homogenized. Additional degassing zones can be applied to remove volatile substances. Furthermore, distributive mixing elements can be applied to distribute particles and dispersive mixing elements can be applied to break up agglomerates[14]. The material leaves the extruder through a die, where the melted plastic is brought into the desired shape.

The extrusion process itself requires at least as much energy as needed to heat and melt the polymeric material. Furthermore, there are losses of the motor drive and gearbox, forced and natural cooling, and the energy needed for auxiliary devices.[16] Most of the existing models to describe single functional zones were developed for pure virgin polymeric materials. When using recycling polymers, some special issues occur. The process is sensitive to the material itself and also to the shape of the raw material. Differing raw material shapes can lead to a strongly changing behavior in the feeding zone [17], in the solids conveying zone [15, 17] and in the delay and melting zone [18]. Mixtures of materials lead to strongly changing behavior, especially in the delay and melting zone [18]. Even small proportions of other materials can significantly decrease the melting capability of a single screw extruder. At the same time, the polymeric material itself may be harmed by increased energy input. Possibly additives must be mixed in to achieve a good quality of the extrudate. To improve the LCA modeling, detailed models describing the recycling process itself and also methods to describe the quality and the applicability of the recycled polymer are needed. In a following step, these models are created.

4.4 Integration and Open Research Questions

The combination of the previously explained methods and tools supports the LCA of plastic recycling processes. As shown in Fig.1, each part delivers specific information. The generic recycling process model guides the user of the assessment template through the assessment process and helps to model the whole recycling process for LCA. It also provides average data for energy consumption, if data of specific process steps is missing. The assessment template is used to collect recycling process data for LCA of existing processes and provides information about the input material quality for the detailed extrusion process model. Finally, the extrusion process model delivers detailed energy consumption data for LCA. Additional outputs of the extrusion process model are the characteristics of the recyclate and energy consumption hot-spots of the extrusion process. Together with the environmental impact results from LCA this information can be used for further process optimization.

The current results are first steps towards more sustainable plastic packaging and there are still some open research questions. One of the most important questions is how all required data for LCA can be acquired? The data collection process is typically very time consuming and sometimes data can not be obtained. Especially in the development process, a fast assessment of the environmental impact of design decisions is required. It would be beneficial to implement a knowledge-base which contains average values for required data and additional information which can be used for an early emission hot-spot evaluation. This would speed up the assessment process. Therefore, a detailed assessment and documentation of common plastic manufacturing and recycling processes regarding their environmental emissions is necessary. Furthermore, existing design guidelines for environmental friendly plastic packaging design should be analyzed with a focus on the end-of-life phase. Another question is, how to deal with uncertain data? Especially in the product development phase it is often not clear, which technologies and machines will be used for manufacturing and recycling. So generic emission factors must be used for LCA in this phase. It would be valuable to know the uncertainty of these factors. Environmental hot-spot processes should also be identified to provide guidance for effective optimization steps. Finally, all these topics must be included in existing development processes of plastic packaging.

5 Conclusion

The use of LCA in the development process of new plastic packaging and for the optimization of plastic recycling processes provides opportunities for the reduction of environmental impacts. First steps towards the use of LCA for plastic packaging are shown in this publication and several open research topics were identified. An important step in conducting LCA is the collection of comprehensive data. Therefore an assessment template was developed which supports the data acquisition and delivers information about material quality and recycling processes. Furthermore, first steps towards a generic recycling process model were made. This generic model contains relevant information for a fast modeling of plastic recycling processes and provides the basis for subsequent LCA. A deeper investigation of the extrusion process, which is an important step of the plastic recycling process, was also performed. Finally, further challenges and open research questions were identified.

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