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The Relevance of Recyclability for the Life Cycle Assessment of Packaging Based on Design for Life Cycle

Jonas Keller [1,*], Carla Scagnetti [1] and Stefan Albrecht [2]

[1] Department Life Cycle Engineering, Institute for Acoustic and Building Physics (IABP), University of Stuttgart, 70563 Stuttgart, Germany; carla.scagnetti@iabp.uni-stuttgart.de

[2] Department Life Cycle Engineering, Fraunhofer Institute for Building Physics IBP, 70563 Stuttgart, Germany; stefan.albrecht@ibp.fraunhofer.de

* Correspondence: jonas.keller@iabp.uni-stuttgart.de

Abstract: The awareness for more environmentally sustainable packaging solutions is steadily growing. With both consumers and manufacturers looking to minimize their impacts on the environment, the need for easy-to-implement and standardized measures strengthening a circular economy rises. In the research, the goal was to determine whether the carbon footprint and circularity of non-food plastic packaging can be improved by simple design changes. The results should then lead to design recommendations, providing a Design for Life Cycle approach. The methodology of the study was to conceptually design a single-use plastic packaging with attributes having positive and negative effects on recyclability. Herein, only design characteristics from products obtainable on the market were regarded. Moreover, a comparison over existing recyclability assessment methods is given. The recyclability was then determined with the selected approach by Cyclos HTP, and a reference calculation was conducted. Life Cycle Assessments were implemented for 14 packaging designs using the GaBi software and the Environmental Footprint method. The results showed that dark color, material compounds, insoluble adhesives, and large labels result in lower recyclability of the single-use packaging. The impacts on climate change range from 0.13 kg CO_2-equivalent emissions (100% recyclability) to 0.21 kg CO_2-equivalent emissions (0% recyclability) per packaging, showing that lower recyclability leads to a larger carbon footprint in all assessed scenarios. Concluding, the research demonstrated that by applying Design for Life Cycle measures, impacts on climate change can be reduced. Lastly, design recommendations for decision makers are outlined.

Keywords: Design for Life Cycle; circular economy; waste management; circular design; plastic packaging; producer responsibility; recyclability; climate change; life cycle assessment

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1. Introduction

The lacking potential of product circularity across all sectors in our economy has been identified as a major environmental concern during the last decades [1]. With consumers asking for more sustainable products and the industry trying to provide environmentally sound yet economic solutions, there is a strong demand for standardized processes and goals [2]. While the EU Circular Economy Action Plan as a part of the European Green Deal aims at defining targets and minimum requirements for the future, the industry is left with the task to meet the requirements [3]. To make these goals achievable and attractive, easy-to-implement approaches are needed. Despite their ease of implementation, such approaches must be backed by scientifically obtained knowledge. Consequently, Life Cycle Assessments (LCAs) are commonly used as a well-suited tool to achieve circular economy goals [4,5].

Though solutions are needed across all sectors, a material considered to have one of the highest potentials and needs for improvement is plastic [6,7]. Not only in recent years, the problems resulting from incorrect handling of plastic waste have been identified to be threatening the environment in a variety of ways [8]. Insufficient collection and waste treatment following the disposal lead to leakage directly into the environment, incineration, or landfilling of the ubiquitous material [9,10]. The topic of plastic pollution and other end-of-life issues have also been picked up by the public since many products made from this material are used by private households [11,12]. An example in this context is plastic packaging [7]. With packaging having the largest share amongst plastic production and it being a fast-rotating consumer good, a societal focus has been set on plastic packaging as an environmental threat [6,11,13]. Despite the immense benefits of plastic packaging to society, the accumulation and treatment of end-of-life plastics are creating a global environmental challenge. To reduce plastic debris in the environment, for example, in the oceans, it has become clear that a focus on design for life and end-of-life is a priority [14]. This concept, also called Design for Life Cycle (DfLC), has been identified to play a major role in minimizing environmental impacts of all kinds of consumer products [15,16].

From the points above, alongside the European Commission's ambitious goal of only introducing recyclable or reusable plastic packing by 2030 as part of a way to a more circular and therefore more sustainable economy, it can be derived that measures are needed to improve the circularity of products [6]. Many properties affect the recyclability of packaging. Among them, the design largely contributes to the performance of the material valorization in further cycles [17]. Therefore, it is one of the main objectives of the DfLC approach to achieve a product design that has the use of the entire product or the materials within a circular economy in mind [18,19].

Thus far, the utilization of plastic materials has mostly been linear [6,20,21]. Given the decreasing reserves of fossil fuels and finite capacity for landfill sites, this linear use of hydrocarbons through packaging and other short-lived applications of plastic is not sustainable [14]. The comfort of disposing of a product rather than reusing or recycling it in addition to the low price and the seemingly unlimited availability promoted a throw-away society [20,22]. Facing the regulatory requirement of developing towards a more circular economy [20], there are several potential solutions to strengthen the weak link between the end-of-life stage of packaging and reuse. With solutions ranging from the substitution of fossil to bio-based resources or the biodegradability of products to immediate reuse by the consumer, approaches for circular products differ widely [14,22]. These approaches are illustrated in Figure 1. Regardless of the chosen approach, the circularity is largely determined during the design stage of the product [23].

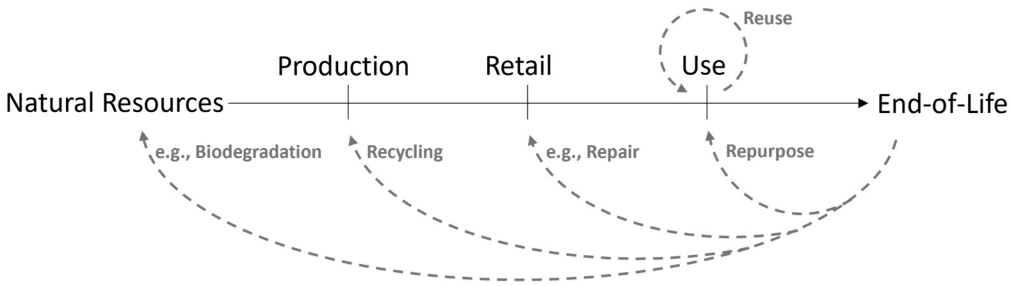

Figure 1. Circularity approaches between disposal and recovery.

To simplify the process of optimizing the circular design of packaging solutions, this paper aims at providing product designers of non-food plastic packaging with easy-to-implement measures. Even though guidelines for environmentally sustainable packaging design based on LCA exist, outlining the specific impacts of certain product characteristics is not common. Product designers are left with requirements or recommendations without knowing the indirect environmental consequences their decisions have. Hence, it is one goal of the study to qualitatively and quantitively evaluate the environmental burdens of a broad spectrum of product designs and characteristics. This is important to build awareness for the impact of design features on environmental performance. Some of the assessed attributes are already known to influence the environmental burdens because of reduced recyclability and therefore circularity. Thus, the motivation for the study is not to create an entirely new guideline but to stress the importance of single measures by providing background knowledge. Herein, only practically relevant technologies are part of the assessment, while scientific fringes are excluded. The specific results are displayed and ranked for all design options considered.

The paper presents the packaging system of a single-use plastic packaging (SUPP) for hygiene products. The objective is to provide a framework for the decision-making process in packaging design. This is achieved through recommendations for improved recyclability and a minimized environmental footprint of the packaging. As the recyclability assessment is always part of an environmental assessment but cannot replace it despite repeatedly observed correlations between the results [24], this study focuses on a coherent structure going from packaging design over the recyclability assessment to LCAs. Moreover, it highlights that a systematic approach using DfLC is crucial to reduce the environmental impacts of the packaging sector. Thus, for the first time, design observations are used directly to emphasize the relevance of DfLC measures via recyclability assessment and LCA. Designers and researchers are provided with tools to substantiate design decisions, as this presents a research gap in current literature.

1.1. Design for Life Cycle

In order to comprehend the environmental impacts caused by the product's design during the stage of development, the field of DfLC delivers methods, tools, and principles for designers, providing lessons learned from already-implemented LCA studies before a specific design is given [16,19]. LCA is defined as the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle [25]. DfLC guidelines, therefore, play hand-in-hand with LCA, with a focus on evaluating the entire life cycle at the design stage. For the approach various names and definitions have been established, all having closed-loop design as a main or subgoal. Some of the more common names for concepts similar to DfLC are design for environment, design for X, design for sustainability, and cradle-to-cradle [18,23,26,27]. As a closed-loop design is one of the main targets of this article, the term DfLC is used, having in mind that other concepts overlap and are part of life cycle approaches as well. DfLC assesses the environmental impacts associated with a product, process, or service throughout its life or duration with hindsight to the design phase. Hence, the DfLC approach saves designers time by pointing out improvement potentials without the need to conduct LCA studies for every possible design option [16]. Nevertheless, the required generalization comes at the price of increased uncertainty, limiting the feasibility of specific DfLC guidelines [16].

In this paper the focus lies on plastic packaging, and hence, DfLC approaches for such are targeted. According to the waste hierarchy established in the EU Directive 2008/98/EC, the avoidance and reduction of used material have the highest priority, followed by the reutilization of the product and material recycling (Figure 2) [28]. However, as the reduction of material is only possible up to a certain degree, and reutilization is not possible for all product categories due to hygiene and commodity requirements, recycling has been identified as the often more feasible option in practice [29]. Therefore, the herein discussed DfLC measures for plastic packaging have a focus on improving recyclability. The overview presented in this paper provides a basis for future development of design-integrated recycling assessments of non-food packaging using life cycle thinking within the guidelines of DfLC. The results of this study can be used to support decision making and highlight the importance of recyclability and input of recycling material, which are required according to the newest EU Guidelines for packaging [6].

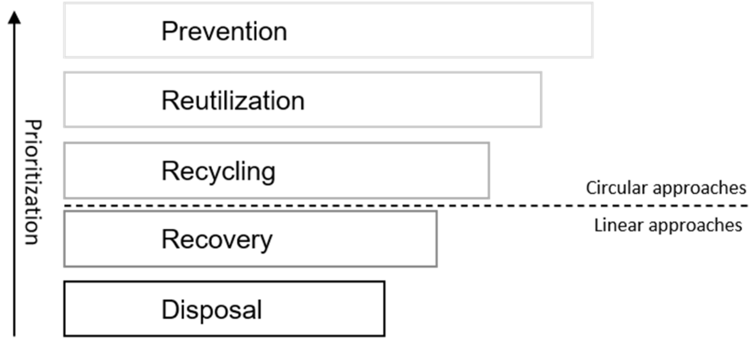

Figure 2. Waste hierarchy, derived from EU Directive 2008/98/EC [28].

1.2. State of the Art Plastics Recycling

The recycled fractions of plastic waste from private households and the used processes and machines vary not only from country to country but are also specific for each recycling plant [30]. Here, the available recycling infrastructure plays a major role in successful recycling. However, some key processes remain largely unchanged and are a part of most facilities. In the following, only a few of these steps in the recycling process, in which the results are directly influenced by common plastic packaging designs, are briefly described and shown in Figure 3.

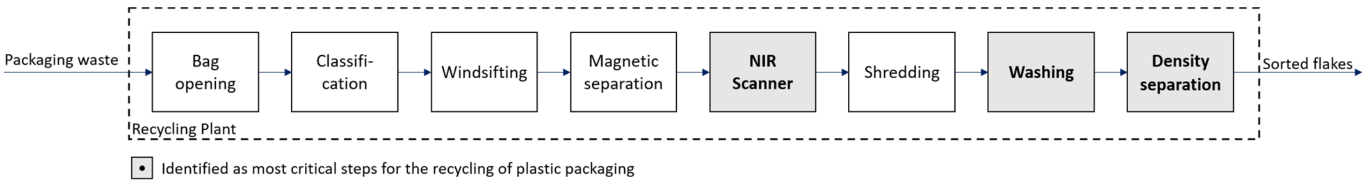

Figure 3. Typical steps of plastic waste recycling in Germany.

One of the central steps in the sorting of plastic packaging waste is the automated sorting by a near-infrared scanner (NIR-Scanner) [31]. Herein, the processed packaging is irradiated with infrared light, and the packaging is separated accordingly by compressed air nozzles [32]. Hindering attributes can be opaque packaging due to low reflection rates, fillers, and compounds as well as labels or sleeves covering the main (target) material [33].

During the washing of plastic packaging, product residues, labels, and other impurities are separated from the targeted material fraction [34]. Most commonly, water-based washing solutions in combination with detergents are used [35]. Some product attributes (e.g., insoluble adhesives or extensive contamination) can hinder the success of the process [33].

Another processing step of importance is the density separation of plastics. Although there are other technologies available, this process is mostly carried out by swim–sink separation [35]. Depending on the material to be recycled, either the swimming fraction (e.g., for PP or PE) or the sinking fraction (e.g., for PET) is processed further [33]. Design flaws, including labels not soluble in the preceding washing process or additives changing the polymer's density, pose a problem for targeted sorting [33,36].

1.3. Review of Recyclability Assessment Methods

To improve the recyclability of a product, it is important to understand how it is determined. Generally, to achieve high recyclability, a product has to be sortable and separable within the currently available recycling infrastructure and must not contain certain contaminants [37]. In addition, the recyclable fraction has to be of high quality to substitute primary raw materials in further cycles [31]. Many recyclability assessment approaches use these requirements to assess the recyclability of packaging [24,38,39]. To break these abstract formulations down to more revisable and therefore more addressable product properties, different approaches have been established to calculate specific degrees of recyclability. A few currently available methods are described below, including their differences, aim, and scope of application. All methods below apply to the geographic reference area of Germany among other European countries. Only the Interseroh scheme applies exclusively to Germany.

Interseroh established the Made for Recycling-label, offering an individual assessment of packaging. Most of the common packaging materials are covered by the analysis, and the product is scored 0 to 20 points in six categories, referring to different steps in the recycling process. The categories are then weighted and result in a single recyclability score [39].

A tool for self-conducted assessments is offered by Henkel, providing a downloadable excel tool (Henkel Easy D4R). Depending on the chosen packaging material, the user selects different characteristics and is given a recyclability class from A to G for the packaging. The method behind the calculation depends on the material and comes either from RecyClass, the University of Vienna, Ceflex, or Henkel [40].

Another method for self-assessing a packaging's recyclability is a web-based tool by RecyClass. Although the tool is only applicable for plastic packaging, it offers a ranking for both the recyclability and the content of recycled material. Differing from the other approaches, the packaging is not only evaluated regarding the compatibility with the recycling processes but also regarding losses during the end-of-life. Results are displayed by a recyclability class from A to F and one to three plus symbols, referring to the amount of used recyclate in the product [38].

The last approach included in the description is the assessment method by Cyclos HTP. Herein, the packaging is rated according to its behavior in the established recycling processes. The scores of the test criteria are then multiplied to a single recyclability score between 0 and 100 and are simplified into recyclability classes AAA+ to C. The method covers all common packaging materials [24].

In summary, the Interseroh tool does not allow for a self-conducted assessment, the Henkel tool does not provide background information about the exact calculation, and the RecyClass method has a limited scope of application. Hence, the recyclability assessment of the exemplary packaging in the following case study used the Cyclos HTP method. Furthermore, since this study's scope is plastic material, a reference calculation using the RecyClass online tool was performed as a form of sensitivity analysis for the recyclability. An overview of the recyclability assessment methods is shown in Table 1.

Table 1. Overview of the reviewed recyclability assessment methods.

	Interseroh	**Henkel**	**RecyClass**	**Cyclos HTP**	
Free self-conducted assessment	No	Yes	Yes	No	
Scale	0–20	A to G	A to F and + to +++	0–100	AAA+ to C
Min. value	0	G	F	0	C
Max. value	20	A	A (+++)	100	AAA+
Reference area	Germany	Europe	Europe	Europe	
Packaging materials covered	Most common materials	Most common materials	Plastic packaging	Most common materials	

The definition of recyclability was also adopted from Cyclos HTP. The definition reads as follows: "Recyclability is the individual, gradual suitability of a packaging or a product to factually substitute material-identical virgin material in the post-use phase; "factually" hereby means that collection and processing structures in industrial scale are available" [24]. In addition, the recyclability of a product is characterized by its environmental and economic value after the product has become waste and assesses the savings through recirculation. As such, it is an independent variable and not an environmental evaluation category. A packaging reaching a recyclability of 100% means that the product meets the requirements to become a secondary product with comparable characteristics to the initial one [24].

2. Materials and Methods

As mentioned before, DfLC guidelines must be backed up by LCA results to verify the environmental performance. Since LCA is only viable for specific design options, an exemplary product system must be regarded. Therefore, as a first step, the exemplary packaging system was specified as a SUPP for hygiene products. The SUPP was chosen due to the non-food content and large variety of existing designs and properties. In the second step of the study, different design options of the product example were conceptualized in order to determine the effects on recyclability and LCA results. The resulting design scenarios vary in different attributes, each scenario having only one attribute affecting the recyclability. In the following step of the research, the compatibility with the existing recycling infrastructure in Europe was evaluated, and the recyclability was assessed using an institute-internal, self-developed tool based on the Cyclos HTP method. The results were verified with the RecyClass method [38], using the provided online tool. In the fourth step of the study, LCAs were conducted for the defined packaging scenarios. The Life Cycle Inventory includes data from literature research and primary data collection from representative exemplars of the product category. For the LCA, the GaBi software version 9.2 was used to model the packaging solutions from cradle-to-grave, and the impact category of climate change was analyzed with the Environmental Footprint method (EF 3.0). The results were then compared in their amplitude and favorable designs are derived, resulting in revaluated design recommendations.

2.1. Calculation of Recyclability

As described in the literature review section, the recyclability calculation assesses the compatibility of a certain product with the available recycling infrastructure. In the method by Cyclos HTP, the formula contains a factor between 0 and 1 for each of the nine regarded steps/criteria, with 1 standing for full compatibility and 0 for no compatibility at all. The product of the factors outputs the recyclability.

The criteria (Cj) are: the allocation to a recycling path (C0), the percentage of recyclable material (C1), the identifiability by the NIR and discharge behavior (C2), the electrical conductivity (C3), the ferromagnetism (C4), the material density after disintegration (C5), the dissolution rate in water (C6), the melting behavior (C7), inseparable contaminants (C8), and additional criteria (C9) [24].

To evaluate the effects of different product attributes on recyclability, 14 scenarios were created. The design variations presented in Table 2 differ in color, amount of used fillers, label size, label material, and used adhesives to address the different calculation criteria (Cj). The base material for all 14 packaging scenarios is polypropylene (PP).

Table 2. Modeling scenarios, SUPP.

Scenario Number	Share of Chalk	Label Size	Label Material	Label Solubility	Color
1	-	20%	PP	Soluble	Transparent
2	-	80%	PP	Soluble	Transparent
3	25%	20%	PP	Soluble	Transparent
4	25%	20%	PP	Soluble	Transparent
5	-	0%	-	-	Transparent
6	-	20%	PE	Soluble	Transparent
7	-	50%	PE	Soluble	Transparent
8	-	80%	PE	Soluble	Transparent
9	-	20%	PE	Insoluble	Transparent
10	-	50%	PE	Insoluble	Transparent
11	-	80%	PE	Insoluble	Transparent
12	-	20%	PP	Soluble	Light color, low translucency
13	-	20%	PP	Soluble	Dark color, low translucency
14	-	20%	PP	Soluble	Black

The attributes of scenarios 3 and 4 do not differ. Nevertheless, two separate scenarios were created as different approaches for the calculation of recyclability are chosen. The calculation of the degree of recyclability was conducted using an institute-internal, self-developed tool based on the Cyclos HTP method. To verify the results, the recyclability for all packaging scenarios was recalculated using the RecyClass method. The drainability was not included into the calculation due to the unavailability of test data. When comparing the results, some differences can be observed, as the RecyClass tool does not consider label size, and outputs result in classes rather than numeric values (Table 3). In addition, using the RecyClass method, recyclability below 50% is only possible through packaging attributes with no compatibility at all and not through a combination of unfavorable characteristics within one assessment category [38]. RecyClass also states that recyclability classes D and E (recyclability below 70%) already indicate a product design not matching the available treatment methods [41]. Nevertheless, the selected attributes have negative effects on the compatibility with the recycling streams according to both calculation approaches, and because of the more precise values, the results from the Cyclos HTP method were used. Scenarios 3 and 4 represent an exception, as significant differences in the degree of recyclability result and the packaging with chalk filler were modeled as two different scenarios, in this case, representing the recyclability assessment approaches. The results are shown in the following Table 3.

Table 3. Recyclability calculation SUPP.

Scenario	1	2	3	4	5	6	7
Recyclability according to Cyclos HTP	100%	100%	-	88%	100%	75%	50%
Recyclability according to RecyClass	>95%	>95%	0.00%	-	>95%	90–95%	90–95%
Scenario	8	9	10	11	12	13	14
Recyclability according to Cyclos HTP	0%	38%	25%	0%	25%	13%	0%
Recyclability according to RecyClass	50–70%	50–70%	50–70%	50–70%	90–95%	50–70%	50–70%

In LCAs, the quality loss during recycling is partially represented by the gradual recyclability, meaning that a lower quality leads to a smaller fraction of the product being recycled. The non-recyclable fraction is modeled as incinerated.

2.2. LCA Case Study

One of the goals of this study is to implement cradle-to-grave LCAs for the different packaging scenarios. The LCAs are conducted for the same design scenarios as presented in the recyclability calculation (Table 2), where an exemplary packaging solution was conceptionally designed with attributes either limiting the recyclability or favorable for the recycling process.

2.2.1. Goal and Scope

To quantify the environmental impacts of any product, a functional unit (FU) must be determined, as it serves as a reference to which the input and output flows are calculated. In addition, system boundaries must be defined to clarify which life stages of the product are assessed and which flows are not reviewed due to minor contributions. A SUPP for hygiene products serves as the exemplary packaging for the LCA. The FU is one hygiene packaging with a mass of 25 g and the main body made from PP (scenarios in Table 2). The exemplary pictures of the assessed product in Figure 4 do not represent the scenarios, as the scenarios were created to show the effects of single attributes rather than representing packaging solutions available on the market.

Figure 4. Exemplary representatives of the SUPP for hygiene products.

At its end-of-life, the SUPP is assumed to be collected from households and sent to a recycling plant. Automated sorting processes and regranulation lead to different success rates in recycling depending on the design of the packaging.

2.2.2. System Boundary

The product system was modeled from the production phase to the end-of life (cradle-to-grave). The process steps described were computed using the GaBi software version 9.2. For most background processes, generic European datasets were used. Where European data were unavailable, German processes are used. Figure 5 gives an overview of the modeled processes. Within the figure, the use phase is grayed out because it is not modeled.

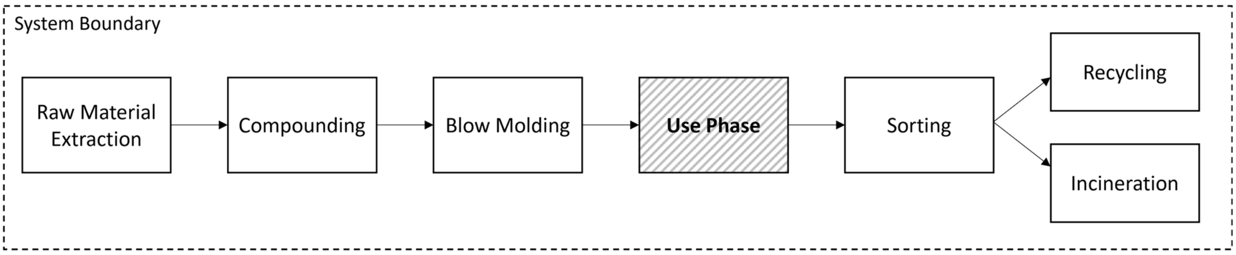

Figure 5. System boundary of the LCA model.

The manufacturing of the SUPP consists of a compounding and a blow-molding step. The use of virgin material is modeled. The use phase of the packaging and transport routes are not included into the model. Having reached its end-of-life, the packaging is sorted and brought to a recycling plant where it is washed, shredded, and re-granulated. Product losses caused by processing or reduced recyclability are modeled as incinerated material shares and result in energy credit. With regards to incineration with thermal recovery, the electricity and thermal energy produced are considered for the European mix using available GaBi datasets. The recycled material share is rewarded with a material credit.

2.2.3. Life Cycle Inventory

The exemplary packaging system in its variations is shown in Table 2. According to the material composition of the packaging, PP and chalk are added to the material mix during the production. The average weight of 25 g is obtained by a series of random weight measurements. Label and color production are not included due to their low weight shares. The electricity country mix dataset for the European Union is used for all data related to energy consumption. The assumption is that the manufacturing and disposal both happen in the EU, with no import or export of plastic waste.

3. Results

For the interpretation of the LCA results, the impact category of climate change was calculated using the EF method by the European Commission [42], which is represented by the EF 3.0 LCIA methodology within the GaBi software. The following Figures 6 and 7 show the LCA results obtained by the model described in the LCA case study. Figure 6 shows the overall results on the impact category of climate change for the regarded scenarios.

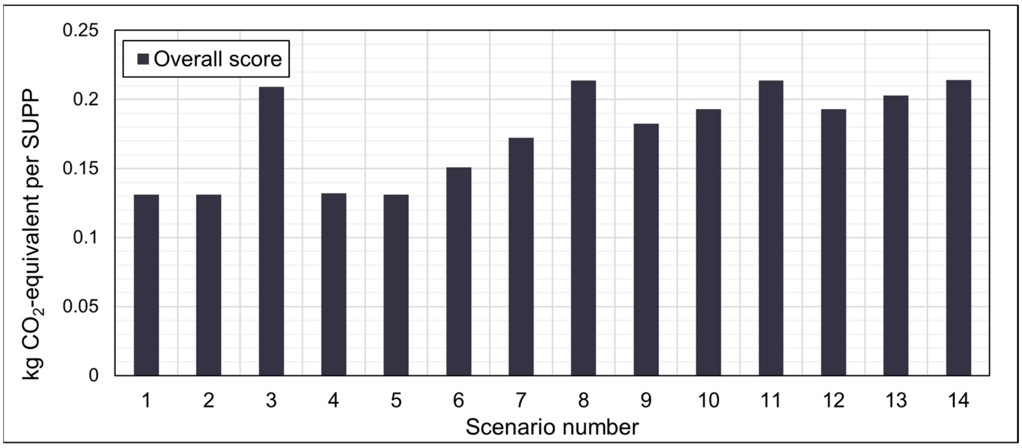

Figure 6. Overall results climate change for the SUPP.

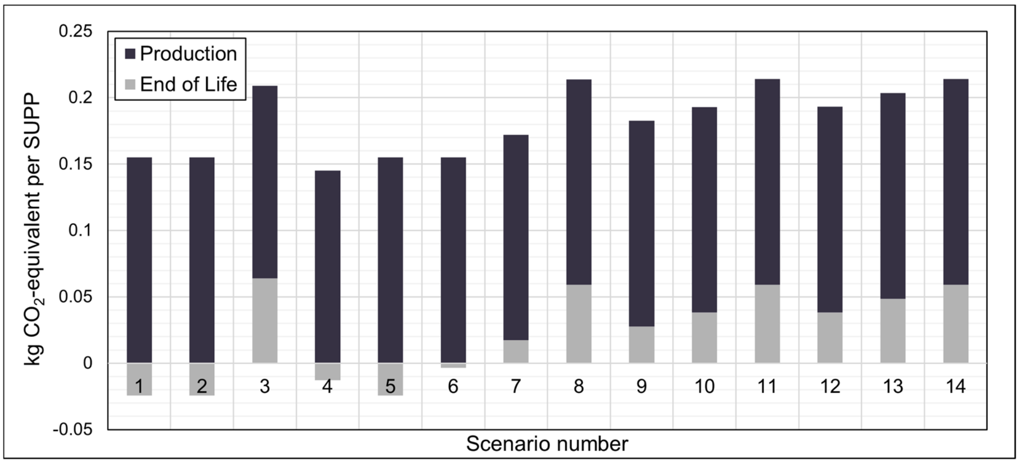

Figure 7. Results climate change by life stages for the SUPP.

To allow for a more detailed analysis of the origin of emissions, the results are split by life stages. In order to do so, processes before the use phase are considered to be part of the production, while processes after the use phase are associated with the end-of-life. Figure 7 thus shows the impacts on climate change split by life stages.

4. Discussion

The displayed results were analyzed regarding their information on certain product characteristics affecting the recyclability and the amount of CO_2-equivalent emissions. Environmentally favorable attributes were then derived from the findings.

Looking at the impact category of climate change, the influence of recyclability becomes clear (Figure 6). Scenarios 1 and 2 show that a label made of the same material as the main body has no impact on the successful sorting and therefore on the CO_2-equivalent emissions, as the label does not lead to missorting during the NIR-stage, and no deduction on C2 within the recyclability calculation occurs. A difference can be seen between scenarios 3 and 4 depending on the underlying degree of recyclability. The results of packaging 4 with a calculated recyclability of 88% do not significantly vary from the ones of scenarios 1 and 2. In comparison with a recyclability of 0% (scenario 3), the impact rises considerably. The reason for this is the assumption within the RecyClass calculation that the density separation is affected, as chalk comes with a higher density than the polymer (deductions on C5). The results of scenarios 5 to 8 show that for labels made from a different material than the packaging, increased label size leads to higher emissions. This is caused by the larger share of missorted packaging by the NIR (deductions on C2) and the reduced recyclability. Correctly sorted packaging faces quality issues due to the material mix (deductions on C8). Nevertheless, the results also show that, compared to scenarios 9 to 11, a water-soluble label results in a lower impact than an insoluble label of the same size. In the calculation, a higher value for C6 for the adhesive and an overall higher C8 occur. Water-soluble labels can be detached partially or fully during the washing process in recycling facilities and lead to a higher C6 factor. The environmental burden also rises for insoluble labels with increased label size, as the washing generally takes place after the NIR-classification, and issues caused by missorting occur as well. The reasons are the same as for soluble labels. The recyclability calculation already showed that the degree of recoverable material decreases with the color strength because of the negative effects on material detection by the NIR-scanner (C2). The results of the LCAs show that the use of colors leads to increased impacts on climate change. Transparent SUPP (scenario 1), on the other hand, has higher recyclability scores and therefore a lower impact.

When the results are broken down by life stage, it can be observed that product scenarios with higher recyclability (e.g., scenarios 1, 2, and 5) are rewarded with credits at their end-of-life due to material recovery (Figure 7). Scenarios with lower recyclability (e.g., scenarios 3, 8, and 14), on the other hand, cause climate change relevant emissions at this life stage due to product shares being incinerated. Energy credits cannot compensate for emissions caused by the incineration. The results for the production are roughly the same throughout the regarded range since label and color production is not part of the life cycle inventory due to their weight shares of 1–2%. Scenarios 3 and 4 cause slightly lower CO_2 emissions during the production phase because the filler chalk has a lower impact on climate change than PP.

Overall, the results show that for all analyzed scenarios, packaging solutions decreasing the sorting success during the recycling process lead to higher impacts on climate change. The discussed results are to be expected, as previous studies already identify mechanical recycling to have less impact on the environment than other end-of-life paths [43,44]. Likewise, the investigated product characteristics are already known to have an impact on recyclability [36,38]. Nevertheless, the specific LCA results for the product attributes are a novel result of the implemented assessment. In such, differences in the sensitivity towards specific changes in design features can be observed. For example, a changed density by fillers can cause very low recyclability and increased environmental burdens at small filler shares (scenario 3). Another finding is that the color of the packaging has the second-largest impact on the environmental burdens for packaging with slightly changed characteristics (scenario 12). After the color, the water solubility of the label shows the largest sensitivity towards changes for packaging with small labels (scenario 9). Moreover, though impacts increase with label size in presence of a soluble adhesive, the environmental burdens do not incline as fast as for other characteristics (scenarios 6 and 7). All the obtained findings related to design characteristics and their environmental consequences add to the knowledge on packaging and DfLC. The observed ranking is strictly specific to the implemented case study.

The results stress the need for SUPP-specific DfLC principles. As product designers do not always have the possibility to implement LCAs, the described results are used to phrase DfLC principles for the regarded product category to simplify the design process. Figure 8 displays a non-hierarchical overview of recommendations based on the results.

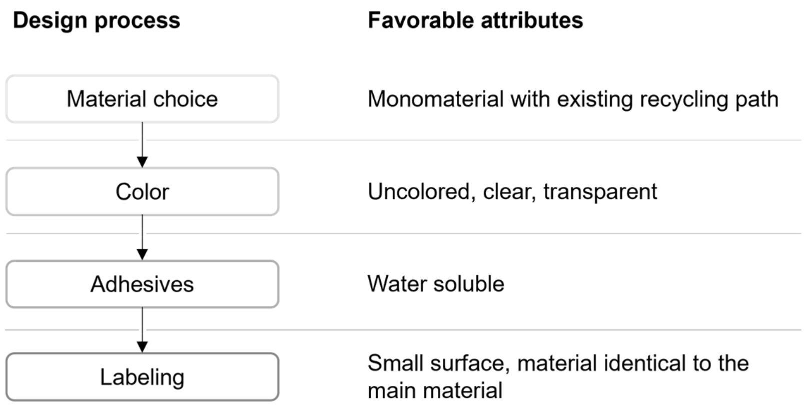

Figure 8. Packaging attributes influencing the recyclability.

Limitations of the Study and Further Steps

Though the results show a clear trend with higher recyclability leading towards a lower impact on climate change, it must be mentioned that the findings represented by the LCA results are limited to the regarded product and scenarios. The results can differ in the case of transferring the methodology to other product systems. Furthermore, the recyclability of specific designs depends largely on the available recycling infrastructure, sorting methods, and collections systems. In this paper and for the underlying recyclability assessment, the current standard technology is taken into consideration, and future development can change the design requirements for high-quality recycling. Since this is a common phenomenon in recyclability assessment studies, recyclability calculation methods are updated frequently. Another relevant characteristic of this study paper is the recyclability assessment of the chalk-filled packaging material since the results output by the institute-internal, self-developed tool differ from the statements towards high-density fillers made by the underlying method of Cyclos HTP [24]. At this point, further research is needed to determine the recyclability of the compound in practice. Quality loss of recyclates is a phenomenon difficult to express in LCA studies at the time of research, and in this paper, it is assumed that there are only recycled and incinerated fractions. Therefore, to take quality losses into account in the calculation, a decreased quality of the recycled material leads to a fraction of the material being incinerated in the LCA though in practice, the entire product might end up as secondary material of lower quality. Further research is needed on how to include quality aspects into LCA not only in packaging-related subjects but in general. In addition, in the study, the collection rate is assumed to be 100%, and landfill is not a potential end-of-life path. The reason for this is goals set by the European Commission aiming to minimize the amount of landfilled plastics [6]. Additionally, littering, as uncontrolled disposal to the environment, and plastic waste exports are not covered as end-of-life paths.

5. Conclusions

The performed analysis of the LCA results shows that increased recyclability leads to reduced environmental burdens within the impact category of climate change for the exemplary product system. To minimize environmental impacts, some product attributes are preferable to others (Figure 8). Generally, fillers, colors, insoluble adhesives, and large labels made of a material differing from the target material should be avoided

In conclusion, the results show that designers of SUPP can improve their products' recyclability by simple measures as part of the DfLC approach while not compromising the content's safety. Many of the observed design characteristics lead to increased contributions to climate change. Thus, the research shows that by applying the steps stated above, environmental burdens can be reduced via target-oriented design processes.

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