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Quality-Driven Allocation Method to Promote the Circular Economy for Plastic Components in the Automotive Industry

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Abstract: In recent years, the development of a circular economy of plastic products in the automotive industry has been pursued by original equipment manufacturers (OEMs) not only due to strategic premises by the European Commission but also due to an increasing demand by customers. To achieve a circular economy, high-quality recyclates are needed. However, in the current situation, there is a discrepancy between the low-quality recyclate that is available on the market and the high-quality recyclate that is demanded by manufacturers. To increase the quality of recyclate on the market, a standardized process to reward a 'design-for-recycling' approach at the product development stage is needed. This paper proposes an allocation method that takes into account material compositions and common recycling processes and incentivizes the preservation of high-quality grades of recyclate based on grade purity.

Keywords: circular economy; life cycle analysis; allocation method; plastic recycling; automotive

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1. Introduction

In recent years, the discussion about the environmental impact of plastic products has increased sharply. In the automotive industry, as one of the largest plastic consumers, there is a growing need for action to develop and implement effective material and component concepts to optimize environmental, social, and governance (ESG) criteria [1,2]. Specifically for plastic components in automotive engineering, various approaches are used to reduce environmental effects, including increasing the quality to extend the lifecycle, reducing energy used in the production stage, using low-emission materials and renewable materials, and reducing material consumption and weight [3,4].

Currently, the demand to substitute the linear economy with a circular economy is also being strengthened [5–7]. The European Commission sees considerable advantages in the circular plastics industry through growth opportunities, the reduction of greenhouse gas emissions, and lower dependence on imported fossil fuels [8]. To increase circularity in the automotive industry, quotas for recyclates from end-of-life vehicles are proposed in the end-of-life vehicles regulation [9].

There are various obstacles to establishing a circular economy for plastic components in automotive engineering. This includes the low quality of recyclate due to contamination and degradation of the polymers [10]. In addition, the exact compositions of the plastics are unknown for many post-consumer recyclates [7,11]. In the current market situation, there is no general lack in the availability of recycled material, but rather a discrepancy between the available low-quality recyclate and the demand for limited, high-quality recyclate, see Figure 1.

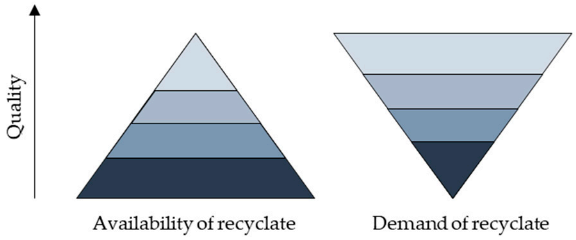

Figure 1. Quality-related availability and demand on the recyclate market.

Another obstacle to a circular economy is the economic perspective. High-quality recyclates can be even more expensive than primary materials and are subject to greater uncertainties in the availability and reliability of the material source [10,12]. Multi-material constructions, which are often used in automotive engineering, require additional disassembly or recycling steps that increase the risk of contamination in the recycled material [11,13,14].

In the automotive industry, many components are generally recyclable, but so far the disassembly process has proven to be uneconomical in practice. In production, several individual parts of different materials are welded, glued, or riveted together, resulting in a module. For assembly and repair purposes, the individual modules are fastened in higher-level assemblies using joints like snap fasteners or screws. A disassembly of individual modules is therefore possible, but disassembling at the level of a single part is associated with high effort and is, therefore, uneconomical. For this reason, only 3–4% of the plastics from end-of-life vehicles are currently recycled [15].

In the recycling process, a tension arises between economic efficiency and quality, as shown schematically for an interior door panel in Figure 2. Feeding entire components into a recycling process results in low-quality recyclates, but sorting by type is hardly feasible [16,17]. However, this process is economically interesting because the effort is low, and no disassembly takes place. If all individual parts are completely dismantled, the process is not economical, but an unmixed recyclate could theoretically be obtained.

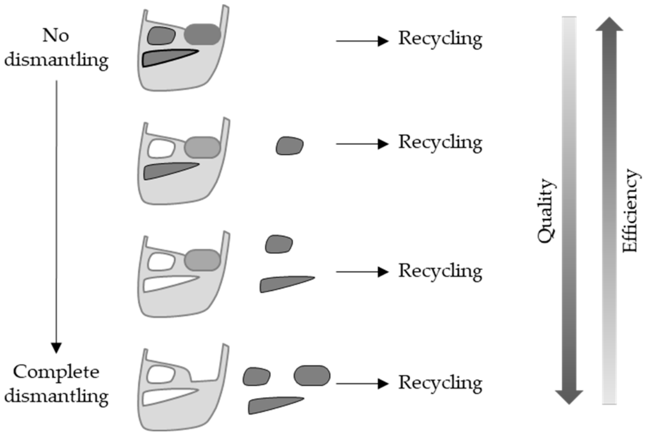

Figure 2. Representation of the quality and economic efficiency of a recycled material depending on the dismantling carried out.

Further obstacles to the establishment of a circular economy lie in the lack of infrastructure, which is indispensable for the economical and scalable recycling of plastic components in the automotive industry [5]. At last, a circular economy requires the need to disclose material compositions [5,11]. This aspect is usually subject to corporate secrets and, thus, is in conflict with competitiveness.

In order to eliminate the strain on the recyclates market and to promote a circular economy, the use of low-quality recyclates and the availability of high-quality recyclates must be promoted. Economic incentives are needed to increase the recyclability of products and to promote the development of recycling infrastructure [18]. The consideration of recyclability in product development must not be generalized but incentivized depending on the quality grade of the recyclate. An effective tool for promoting recycling-friendly product designs is economic incentives by giving CO_2-eq credits.

The incentives given for recyclability and the use of recyclates strongly depend on the allocation method used. Plastic components in the automotive industry lack a definition for recyclability and, therefore, a standardized method for consideration in a life cycle analysis (LCA). This paper gives an overview of common allocation methods and the incentives given for recyclability. Furthermore, requirements to promote a circular economy are discussed, and an allocation method to standardize the incentive for the recyclability of plastic components in the automotive industry is proposed. This new allocation method allows a quality-oriented classification of the recyclability of components in the automotive industry, which previous allocation methods do not take into account, as they are either general or tailored to the packaging industry. By linking recyclability and CO_2-eq credit, quality criteria become quantifiable and ultimately assessable in monetary terms.

2. Results

2.1. Overview of Common Allocation Methods

The execution of a LCA is described in DIN EN ISO 14040:2021-02 [19] and DIN EN ISO 14044:2021-02 [20]. The standards outline the global process for creating a LCA, but do not refer to different use cases. This means that only a framework is provided, but no precise regulations for creating a LCA are specified. Depending on the choice of system boundaries, functional units, databases, or allocation methods, an individual LCA may not be comparable and may even yield opposite results.

The common allocation methods of cut-off, 50:50, disposal and extraction load, loss-of-quality, and the regulation by the European Commission for the calculation of environmental footprints (EC-EF) account for the recyclability to varying degrees. For a detailed description of various allocation methods, please refer to [21–25]. The allocation according to the cut-off method is exemplified in Figure 3 by color-coding the load distribution, L_i, of a chain of three producers and is calculated according to Equations (1)–(3).

$$L_1 = V + P_1 \tag{1}$$

$$L_2 = R_1 + P_2 \tag{2}$$

$$L_3 = R_2 + P_3 + W \tag{3}$$

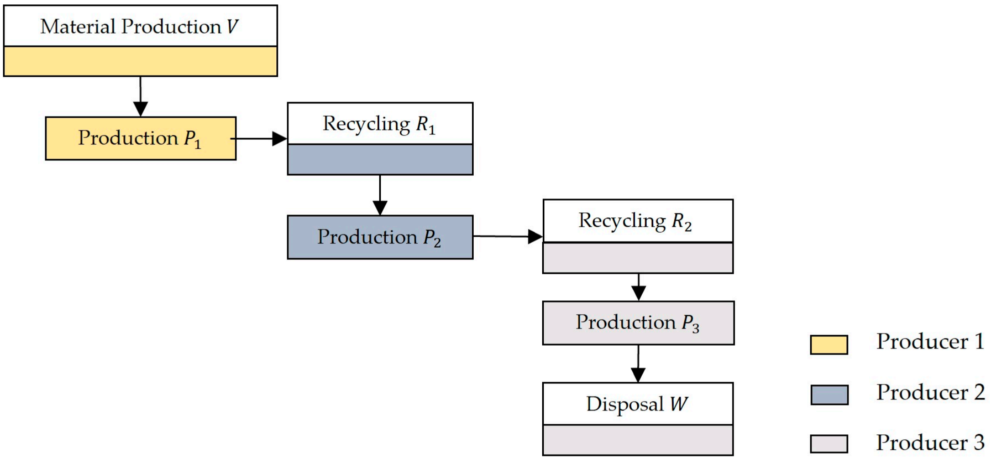

Figure 3. Exemplary load distribution among three producers according to the cut-off allocation method.

Producer 1 uses primary material but produces a recyclable product and, therefore, bears the costs, L_1, resulting from material production, V, and the component production process, P_1. Producer 2 uses recycled material from process R_1 and also produces a recyclable component, thus has to bear the load, L_2, which includes the preceding recycling process, R_1, as well as the loads of its own production process, P_2. Producer 3 uses recycled material from process R_2, but its product is not recyclable. It shall, therefore, bear the loads, L_3, consisting of the preceding recycling process, R_2, the production process, P_3, and disposal of the material, W. The calculations of other common allocation methods for the given example in Figure 3 are presented in Table 1.

Table 1. Calculation of burden sharing for the chosen example of the production chain shown in Figure 3 using different allocation methods.

Allocation Method	L_1	L_2	L_3
50:50	$0.5{\cdot}V + P_1 + 0.5{\cdot}R_1 + 0.5{\cdot}W$	$0.5{\cdot}R_1 + 0.5{\cdot}R_2 + P_2$	$0.5{\cdot}V + P_3 + 0.5{\cdot}R_2 + 0.5{\cdot}W$
Extraction load	$V + P_1 + W$	$R_1 + P_2$	$R_2 + P_3$
Disposal load	$P_1 + R_1$	$R_2 + P_2$	$V + P_3 + W$
Loss-of-Quality	$P_1 + \Delta Q_1(V + R_1 + R_2 + W)$	$P_2 + \Delta Q_1(V + R_1 + R_2 + W)$	$P_3 + \Delta Q_1(V + R_1 + R_2 + W)$
EC-EF	$0.55{\cdot}V + P_1 + 0.5{\cdot}R_1$	$0.5{\cdot}R_1 + 0.5{\cdot}R_2 + P_2$	$0.45{\cdot}V + 0.5{\cdot}R_2 + P_3 + W$

Depending on the allocation method, the use of recycled material and the recyclability of a product are rewarded differently. If the user of the recyclate bears the burden of the recycling process, the use of high-quality post-industrial recyclate is more beneficial to the global warming potential (GWP) than the use of low-quality post-consumer recyclate. This is due to the more complex and energy-intensive recycling process of post-consumer waste.

In the cut-off approach, the disposal load, the 50:50 method, and EC-EF, the disposal step is borne entirely or at a general share of 50% by the last producer (Producer 3). An incentive for recycling-friendly product designs is therefore only reflected by the elimination of the load of disposal. However, the quality of the recycled material is not relevant. Producers can, therefore, develop their products in such a way that only the minimum criteria for the fulfillment of recyclability are met, which leads to low-quality recyclate or high costs in the recycling process. In the extraction load method, the step of disposal is already covered by the first producer (Producer 1), so the recyclability of a product does not bring any benefits. The loss-of-quality method allocates the burden of disposal on a proportionate basis to all producers according to the quality difference between input and output material ΔQ. However, there are no clear guidelines for quantifying the quality. Another feature of the methodology is the complete division of all recycling cycles. This can work in a closed circuit, but in an open system, the number of recycling cycles is unknown. None of the common allocation methods create a viable approach that maintains the recyclate in the material cycle at a high quality for as long as possible.

The allocation method described in EC-EF takes into account the quality difference between input and output material [25]. In particular, values defined for the packaging and construction industry are given depending on the type of material and component. In contrast to packaging and construction, the components of the automotive industry consist of complex and diverse material and component assemblies that must first be dismantled. The quality difference between input and output material, therefore, depends not only on the material composition but also on the component periphery and the economic efficiency of the disassembly process. To purposefully promote a circular economy, these factors must be considered when it comes to the rating of recyclability and the rewarding of credits in a LCA.

2.2. Requirements for an Allocation Method to Promote a Circular Economy

When developing an allocation method to promote the circular economy for plastic parts in automotive engineering, the following aspects must be considered:

- provide a clear definition of recyclability;
- put the responsibility for the recycling process on the producer's side;

- allocate material production and disposal to all parties involved along the production chain;
- define the quality difference between input and output based on circular capability.

Based on the presented allocation methods, a new allocation method is proposed that implements these requirements to promote a circular economy for plastic components in the automotive industry. This allocation method, according to Equation (4), is shown schematically in Figure 4, where the shift of the load shares depending on ΔQ_i is presented by arrows.

$$L_i = R_i + (V + W) \cdot \Delta Q_i \tag{4}$$

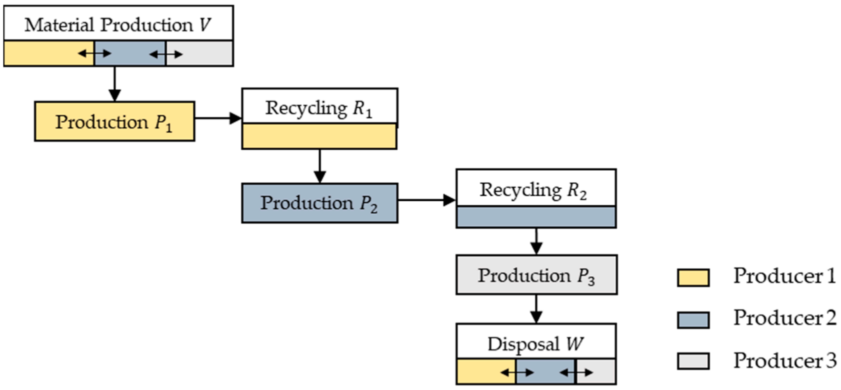

Figure 4. Proportionate load distribution among Producers 1, 2, and 3 according to the proposed allocation method.

The most important criterion for building a circular economy is the recyclability of products. Criteria for recyclability must be precisely defined enough to ensure a uniform understanding and a regulated allocation of loads. Recyclability cannot be related solely to the homogeneity of the products; without the necessary infrastructure, like corresponding collection stations, sorting facilities, and recycling options, no recycling can take place. A product can only be classified as recyclable if the corresponding infrastructure and logistics exist at the time of recovery and at the place of recovery. Based on the definition of recyclability of packaging, credits for recyclability can only be given if the following requirements are met at the time of disposal [26,27]:

- There is existing infrastructure for collecting and sorting the relevant components;
- Recycling incompatibilities are absent;
- The material composition of the component is known.

Theoretical recyclability without the presence of an infrastructure is not to be classified as recyclability.

There are various methods for assigning responsibility for the recycling process. However, the effort involved in the recycling process depends not only on the demanded quality of the recyclate but primarily on the material composition and component structure. The material composition can only be influenced by the previous producer. If the burden of the recycling process is charged upstream to the producer of the component that needs to be recycled, energy-efficient processes are beneficial and, thus, easily recyclable material compositions are incentivized. In the proposed allocation method (Figure 4), the recycling process (Recycling R_i) is therefore assigned upstream to the distributor of a recyclable product. In this example, this means that Producer 1 (Production P_1) bears the load of recycling process 1 (Recycling R_1) and Producer 2 (Production P_2) bears the load of the recycling process 2 (Production R_2).

Along the chain of producers 1–3 (Production P_i), everyone benefits from the fact that the material is produced and ultimately disposed of. The re-introduction of recycled material into the technosphere through appropriate recycling causes proportional damage to the material and results in a loss in quality. Even the first members of the recycling chain must be given incentives to keep the material quality at a high level for as long as possible.

In the proposed allocation method, material production V and disposal W is distributed proportionately among all producers along the chain. The division is based on the delta of defined quality criteria, ΔQ_i, that consider the separability of materials.

Two conditions must be met for the recyclability of plastic components in end-of-life vehicles: improvement of sorting systems to separate complex material compositions and consideration of existing sorting and recycling technologies in material selection and component development [15]. If the materials cannot be completely separated, residues remain in the recyclate, resulting in a deterioration in quality. The incompatibility of material compounds may be caused by chemical incompatibility or incompatibility of the processing parameters. In addition to the incompatibility of the material composition, the loss of properties is also influenced by the aging of the material.

In the analysis of recyclability, grade mixture, separability, and compatibility of input material composition are crucial. A component consisting of only one material type offers the highest quality. Separability and compatibility of material types in a component are important criteria for obtaining high-quality recyclates. In the proposed allocation method, the load to be borne for material production and disposal is set in proportion to the difference in quality between the recycled material used and the recyclate made from the component at the end of the product life. As a result, rewards are given for providing easily recyclable components. The level of recyclability must, therefore, be directly considered in the development of components. To achieve a high-quality level of recyclate, a consideration between economically feasible dismantling and recyclable material composition must be made.

If the material composition does not suffer any loss in quality due to the component composition and subsequent recycling and, thus, remains at the same quality level of homogeneity, a share of 10% is still to be counted to compensate for material aging. Plastic is not infinitely recyclable and must be disposed of after structural degradation. Due to an expense of 10%, the segregated material would be ecologically depreciated after nine recycling cycles and can be removed from the technosphere. This value corresponds to the factor of 0.9 that is currently required in the EU directive for the remaining quality of polypropylene components over one recycling cycle [25].

The categorization of the recyclability of plastic components according to quality levels is shown in Table 2. Quality level 1 here corresponds to the virgin material. Virgin material, therefore, represents the highest quality level. Quality level 2 describes the segregated material composition. Unmixed-grade recyclates (e.g., polypropylene (PP)) represent the highest quality among recyclates. This category also includes commonly used polymer blends such as polycarbonate/acrylonitrile-butadiene-styrene (PC-ABS) [28]. They have a modified property profile due to the mixing of two or more types of plastic.

Table 2. Quality levels and credit assignment for categorization of material compounds in recycling.

Quality Level	Credit	Category	Example
1	100%	Virgin material	-
2	80%	Unmixed material	PP, PC-ABS
3	60%	Separable and compatible materials	PC and ABS
4	40%	Separable materials with limited compatibility	PP and PC-ABS
5	20%	Non-separable but compatible materials	PP + TPO
6	0%	Neither separable nor compatible materials	PP + PU + PVC

Separable and compatible material compositions represent quality level 3 and can be separated into their individual material types. In this case, requirements for the sorting technology are low because small remains of the other material do not have a negative effect on the property profile (e.g., PP and ABS). In contrast to quality level 2, the recycled material produced is not a plastic blend. The individual materials are, therefore, not chemically matched with each other. However, due to the compatibility of the materials, contamination does not have a negative impact on the property profile or processability.

Quality level 4 comprises separable materials mixtures with limited compatibility (e.g., PP and PC-ABS). They place high demands on the sorting technology, as there is a risk of incomplete separation of the materials and a deterioration in the property profile. However, up to a certain degree of contamination, the recyclates can have high mechanical properties similar to the primary polymer [15].

Quality level 5 represents non-separable but compatible materials (e.g., bonded PP and thermoplastic polyolefin (TPO)). While the materials are not separable, they can be processed together into new products. In the plastic industry, the presence of safe sources and consistent qualities is essential. Material compositions that are inherently compatible but not commonly available on the market do not provide a large-volume and consistent source and can, therefore, usually only be reused in special applications. The incorporation of such material compositions requires a high adaptation of the formulation and is, therefore, of little interest.

The final stage, quality level 6, consists of material compositions that are incompatible and inseparable (e.g., bonded PP with polyurethane (PU) and polyvinylchloride (PVC)). They have to be used for incineration or for untypical applications.

3. Discussion

3.1. Exemplary Application of the New Allocation Method for Automotive Components

The proposed allocation method is explained in Figure 5, using three scenarios. Three PP door carriers with 20% glass fibers (GF) are considered. Each carrier weighs 0.7 kg and is made of virgin material, differing only in the component periphery and, therefore, the recyclability. In scenario 1, a fully disassembled door carrier made of PP-GF is analyzed. In scenario 2, the door carrier contains a cover made of PC-ABS that is welded on and cannot be removed. In scenario 3, the basic door carrier is laminated with a TPO film.

- Scenario 1: completely disassembled door carrier made of PP-GF;
- Scenario 2: disassembled door carrier made of PP-GF, including a welded-on panel made of PC-ABS;
- Scenario 3: completely disassembled door carrier made of PP-GF with a laminated TPO film.

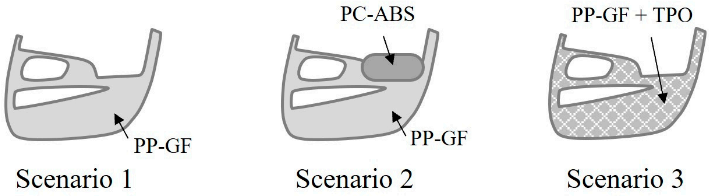

Figure 5. Selected scenarios for the exemplary application of the proposed allocation method.

For better comparability, only the door carrier is considered in the LCA. The panel and the laminated TPO film are not included in the balance sheet and are only used for classification into a quality grade. The data used to calculate the LCA are shown in Table 3.

Table 3. Assumed values for the preparation of the LCA [29–32].

Nomenclature	Symbol	Value
Polypropylene	GWP_{PP}	1.63 kg CO_2-eq/kg
Glass fiber	GWP_{GF}	2.42 kg CO_2-eq/kg
Energy consumption in injection molding	E_{Inj}	1.2 kWh/kg
GWP of energy grid mix (green energy)	GWP_{egm}	0.0275 kg CO_2-eq/kWh
Energy consumption in recycling	E_{Rec}	0.7 kWh/kg
Component mass	m	0.7 kg
GWP of incineration	GWP_{Inc}	3.14 kg CO_2-eq/kg
Energy reduction value	ERV	0.6 kWh/(100 kg·100 km)

The calculation of the LCA is performed based on the Equations (5)–(9). The calculation of the use phase, U, is adapted for a battery-electric vehicle (BEV) based on the derivation in [33] for a mileage of 200,000 km.

$$V = m \cdot GWP_{PP-GF} = 0.8 \cdot m \cdot GWP_{PP} + 0.2 \cdot m \cdot GWP_{GF} \tag{5}$$

$$R = m \cdot GWP_{egm} \cdot E_{Rec} \tag{6}$$

$$P = m \cdot GWP_{egm} \cdot E_{Inj} \tag{7}$$

$$W = m \cdot GWP_{Inc} \tag{8}$$

$$U = m \cdot \frac{ERV}{100 \text{ kg} \cdot 100 \text{ km}} \cdot 200,000 \text{ km} \tag{9}$$

The balance of the incineration does not include energy recovery since the credit benefit of energy recovery will be drastically reduced due to the substitution of fossil energy sources for renewable energy sources.

For reference, a non-recyclable door carrier is considered, which has a total GWP of 3.26 kg CO_2-eq, including material production V, component manufacturing P, use phase U and incineration of the PP-content W. The glass fiber content cannot be incinerated. For material production, component manufacturing, use phase, and incineration, the premises and the calculations are equal in all scenarios. Only the rewards given for recyclability in the balance of material production and disposal, i.e., incineration, differ.

In the ideal scenario 1, the door carrier can be completely dismantled and reused as an unmixed recyclate with $\Delta Q_i = 0.8$, reducing the GWP to 0.87 kg CO_2-eq. In scenario 2, a removable door carrier with an inseparably applied panel made of PC-ABS is considered, resulting in a classification of quality level 4 with $\Delta Q_i = 0.4$, which increases the GWP by 1.2 kg CO_2-eq compared to scenario 1, to a total of 2.07 kg CO_2-eq. In scenario 3, the door carrier can be completely dismantled but is laminated with a TPO film and can therefore be assigned to quality level 5 with $\Delta Q_i = 0.2$. This results in a GWP of 2.67 kg CO_2-eq, which still leads to an 18% lower GWP compared to the reference component. The detailed results are shown in Figure 6.

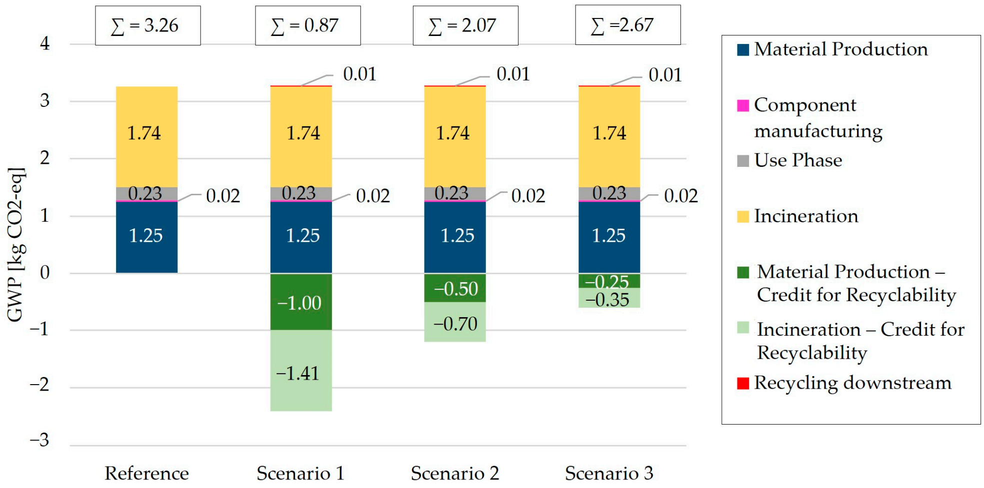

Figure 6. LCA for the selected scenarios 1–3 using the proposed allocation method.

3.2. Assumptions and Limitations of the Proposed Allocation Method

We made the following assumptions when developing this allocation method:

- The market for recyclates remains tense, and OEMs must push for the reuse of their own plastic components from end-of-life vehicles out of self-interest or due to political demands;
- Reducing the eco-balance in vehicle production remains a development goal;

- Incentivizing recycling processes through CO_2 credits is an efficient method of promoting the use of recyclates in new products;
- The processing of plastic components into unmixed recyclates represents a major challenge in the reuse of recyclate from end-of-life vehicles;
- Improving the recyclability of products through the preferential use of chemically compatible plastic materials leads to the creation of economically interesting high-quality recyclates;
- Different plastics allow a percentage comparison value to be derived for the quality loss, which can be incorporated into the allocation method as the quality level of the material. The recyclability of plastic products can be described meaningfully and effectively with the help of quality levels and taken into account mathematically by introducing a percentage quality reduction in LCA;
- Redistribution of the burden for the recycling process and material disposal down the production chain ensures increasing product responsibility for the respective producer and creates additional incentives to use materials and material combinations with high recyclability;
- The necessary data are generated and made available to the recycler.

When using this allocation method for the life cycle assessment of automotive components, its limitations must also be taken into account. Some key points from the authors' perspective are defined below:

- Chemical recycling of plastics cannot be balanced with the proposed method;
- If the required product quality cannot be achieved with chemically or physically compatible and easily recyclable material combinations and makes the use of material combinations that are unfavorable for recycling unavoidable, the new allocation method is ineffective;
- The proposed method allows quality grading in 20% increments. It is, therefore, not possible to carry out a more detailed assessment within these quality levels;
- Different degrees of degradation of different types of plastic are not considered. Chemically different plastics such as PP, ABS, PET, or PBT degrade at different rates and in different ways as a result of recycling and reuse. In order to quantify this fact using the allocation method, further quality gradations or correction factors must be introduced depending on the type of material.

4. Conclusions

In contrast to common allocation methods, the new allocation method defines quality criteria depending on material compositions and component periphery for the automotive industry. The proposed allocation method offers an approach for quality-dependent incentivization of recyclability and expands the methodology specified by the EU to include the classification of component groups in quality levels and the greater weighting of the disposal phase. Since developing cycles in the automotive industry are fairly long, a market-dependent factor cannot be considered.

If recyclability is already considered during component development, it is not only possible to reduce the GWP in the long term but also to improve the availability of high-quality recyclate. Recyclability must not be limited to individual components but must be considered holistically, considering economic factors and common recycling processes. A recyclable component that can only be reused due to a very high effort for disassembly and separation does not represent an economically feasible procedure. If tailored boundaries of module groups are already drawn during component development, the actual recyclability can be increased through efficient and targeted disassembly processes. The relatively narrow limits of a one-door carrier in the scenarios considered can be extended to other components of a door panel, such as the door center panel or the beltline. If entire components are constructed of only a few but easily separable materials, simple recycling processes, such as density separation, can be used.

The proposed allocation method can be used for plastic components in automotive engineering. For this purpose, further investigations must be carried out to describe the quality categories more precisely. Due to the long development and usage times of a vehicle, the credit calculated remains theoretical and cannot be calculated on the basis of real material flows. However, the methodology provides incentives for recycling-friendly design and can, therefore, influence the establishment of a circular economy in the automotive industry. For the implementation of the allocation method, a database is required to define guidelines on material compatibility and separation. A reliable, consistent, and easily accessible database on the materials used is also essential for reuse in order to select suitable recycling processes and minimize contamination [34].

The automotive industry has a worldwide aggregated demand for plastics of roughly 30 Mt/year, which accounts for 8% of the total plastic demand [35]. If the necessary requirements considering the recycling infrastructure and data platforms are met and a design-for-recycling approach is considered during the development of automotive plastic components, the strain on the recyclate market can be loosened, which results in saving fossil resources and drastically reduces the carbon footprint of the plastic industry.

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References

1. Hallack, E.; Peris, N.M.; Lindahl, M.; Sundin, E. Systematic Design for Recycling Approach—Automotive Exterior Plastics. *Procedia CIRP* **2022**, *105*, 204–209. [CrossRef]
2. Vieyra, H.; Molina-Romero, J.M.; Calderón-Nájera, J.D.D.; Santana-Díaz, A. Engineering, recyclable, and biodegradable plastics in the automotive industry: A review. *Polymers* **2022**, *14*, 3412. [CrossRef] [PubMed]
3. Barillari, F.; Chini, F. Biopolymers—Sustainability for the Automotive Value-added Chain. *ATZ Worldw.* **2020**, *122*, 36–39. [CrossRef]
4. Menzel, C.; Stamp, B.; Kroll, L.; Rinberg, R.; Blumenstock, T.; Bieder, H. Schlanker Materialmix für leichtes Interieur. *Kunststoffe* **2017**, *5*, 90–93.
5. Van Bruggen, A.R.; Zonneveld, M.; Zijp, M.C.; Posthuma, L. Solution-focused sustainability assessments for the transition to the circular economy: The case of plastics in the automotive industry. *J. Clean. Prod.* **2022**, *358*, 131606. [CrossRef]
6. Soo, V.K.; Compston, P.; Doolan, M. Is the Australian automotive recycling industry heading towards a global circular economy?—A case study on vehicle doors. *Procedia CIRP* **2016**, *48*, 10–15. [CrossRef]
7. Baldassarre, B.; Maury, T.; Mathieux, F.; Garbarino, E.; Antonopoulos, I.; Sala, S. Drivers and barriers to the circular economy transition: The case of recycled plastics in the automotive sector in the European Union. *Procedia CIRP* **2022**, *105*, 37–42. [CrossRef]
8. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A European Strategy for Plastics in a Circular Economy. COM(2018) 28 Final. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2018:28:FIN (accessed on 21 May 2024).
9. Proposal for a Regulation of the European Parliament and of the Council on Circularity Requirements for Vehicle Design and on Management of End-of-Life Vehicles, Amending Regulations (EU) 2018/858 and 2019/1020 and Repealing Directives 2000/53/EC and 2005/64/EC. COM(2023) 451 Final. Available online: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:52023PC0451 (accessed on 21 May 2024).
10. Pfisterer, I.; Rinberg, R.; Kroll, L. Investigation of material degradation during multiple recycling loops of a glass fiber reinforced polypropylene compound to evaluate life cycle analysis based on mechanical properties. *Technol. Lightw. Struct.* **2021**, *5*, 61–68. [CrossRef]
11. Miller, L.; Soulliere, K.; Sawyer-Beaulieu, S.; Tseng, S.; Tam, E. Challenges and alternatives to plastics recycling in the automotive sector. *Materials* **2014**, *7*, 5883–5902. [CrossRef]

12. Shamsuyeva, M.; Endres, H.J. Plastics in the context of the circular economy and sustainable plastics recycling: Comprehensive review on research development, standardization and market. *Compos. Part C Open Access* **2021**, *6*, 100168. [CrossRef]
13. Buekens, A.; Zhou, X. Recycling plastics from automotive shredder residues: A review. *J. Mater. Cycles Waste Manag.* **2014**, *16*, 398–414. [CrossRef]
14. Rinberg, R.; Hartenstein, M.; Kroll, L. Pedelecs und Cargo-Pedelecs als umweltfreundliche Mobilitätsalternative in urbaner Umgebung. *J. Mobilit. Verk.* **2022**, *15*, 18–24. [CrossRef]
15. Froelich, D.; Maris, E.; Naoues, N.; Chemineau, L.; Renard, H.; Abraham, F.; Lassartesses, R. State of the art of plastic sorting and recycling: Feedack to vehicle design. *Miner. Eng.* **2007**, *20*, 902–912. [CrossRef]
16. Zhang, H.; Chen, M. Current recycling regulations and technologies for the typical plastic components of end-of-life passenger vehicles: A meaningful lesson for China. *J. Mater. Cycles Waste Manag.* **2014**, *16*, 187–200. [CrossRef]
17. Tian, J.; Chen, M. Sustainable design for automotive products: Dismantling and recycling of end-of-life vehicles. *Waste Manag.* **2014**, *34*, 458–467. [CrossRef]
18. Zheng, J.; Suh, S. Strategies to reduce the global carbon footprint of plastics. *Nat. Clim. Change* **2019**, *9*, 374–378. [CrossRef]
19. *DIN EN ISO 14040:2021-02*; Environmental Management—Life Cycle Assessment—Principles and Framework (ISO 14040:2006 + Amd 1:2020). Deutsches Institut für Normung e.V. (DIN): Berlin, Germany, 2021. Available online: https://www.dinmedia.de/de/norm/din-en-iso-14040/325953744 (accessed on 30 May 2024).
20. *DIN EN ISO 14044:2021-02*; Environmental management—Life Cycle Assessment—Requirements and Guidelines (ISO 14044:2006 + Amd 1:2017 + Amd 2:2020). Deutsches Institut für Normung e.V. (DIN): Berlin, Germany, 2021. Available online: https://www.dinmedia.de/de/norm/din-en-iso-14044/325953813 (accessed on 30 May 2024).
21. Nicholson, A.L.; Olivetti, E.A.; Gregory, J.R.; Field, F.R.; Kirchain, R.E. End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions. In Proceedings of the 2009 IEEE International Symposium on Sustainable Systems and Technology, Tempe, AZ, USA, 18–20 May 2009. [CrossRef]
22. Rehberger, M.; Hiete, M. Allocation of Environmental Impacts in Circular and Cascade Use of Resources—Incentive-Driven Allocation as a Prerequisite for Cascade Persistence. *Sustainability* **2020**, *12*, 4366. [CrossRef]
23. Ekvall, T.; Tillman, A. Open-Loop Recycling: Criteria for Allocation Procedures. *Int. J. LCA* **1997**, *2*, 155–162. [CrossRef]
24. Allacker, K.; Mathieux, F.; Pennington, D.; Pant, R. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *Int. J. LCA* **2017**, *22*, 1441–1458. [CrossRef]
25. European Commission, European Platform on LCA EPLCA. The Product Environmental Footprint Category Rules (PEFCR ver. 6.3). Available online: https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf (accessed on 30 May 2024).
26. Stiftung Zentrale Stelle Verpackungsregister. Minimum Standard for Determining the Recyclability of Packaging Subject to System Participation Pursuant to Section 21 (3) VerpackG. Available online: https://www.verpackungsregister.org/fileadmin/files/Mindeststandard/Minimum_standard_Packaging-Act_2022.pdf (accessed on 23 May 2024).
27. Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and chemical recycling of solid plastic waste. *Waste Manag.* **2017**, *69*, 24–58. [CrossRef] [PubMed]
28. Kuram, E.; Ozcelik, B.; Yilmaz, F. The effects of recycling process on thermal, chemical, rheological, and mechanical properties of PC/ABS binary and PA6/PC/ABS ternary blends. *J. Elastomers Plast.* **2016**, *48*, 164–181. [CrossRef]
29. Plastics Europe AISBL. Eco-Profiles Program and Methodology: Version 3.0. Available online: https://plasticseurope.org/wp-content/uploads/2021/12/PlasticsEurope-Ecoprofiles-program-and-methodology_V3.0.pdf (accessed on 30 May 2024).
30. German Federal Office for Economic Affairs and Export Control (BAFA). Informationsblatt CO2-Faktoren: Bundesförderung für Energie- und Ressourceneffizienz in der Wirtschaft—Zuschuss: Version 1.1. Available online: https://www.bafa.de/SharedDocs/Downloads/DE/Energie/eew_infoblatt_co2_faktoren_2021.html (accessed on 30 May 2024).
31. Kent, R. *Energy Management in Plastics Processing: Strategies, Targets, Techniques, and Tools*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 33–78. [CrossRef]
32. Del Pero, F.; Berzi, L.; Antonacci, A.; Delogu, M. Automotive lightweight design: Simulation modeling of mass-related consumption for electric vehicles. *Machines* **2020**, *8*, 51. [CrossRef]
33. Rohde-Brandenburger, K. Was bringen 100 kg Gewichtsreduzierung im Verbrauch? Eine physikalische Berechnung. *ATZ Automobiltech. Z.* **2013**, *115*, 584–591. [CrossRef]
34. Duval, D.; MacLean, H.L. The role of product information in automotive plastics recycling: A financial and life cycle assessment. *J. Clean. Prod.* **2007**, *15*, 1158–1168. [CrossRef]
35. Plastics Europe AISBL. Plastics—The Facts 2022. Available online: https://plasticseurope.org/wp-content/uploads/2023/03/PE-PLASTICS-THE-FACTS_FINAL_DIGITAL-1.pdf (accessed on 30 May 2024).