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Novel methodology for the selection and evaluation of R-strategies to support product design for circular economy

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Abstract: EU legislation demands manufactures to improve their product's circularity. The 9R Framework organizes strategies of a circular economy in a hierarchical manner based on their respective effectiveness in promoting circularity. Manufacturers need to determine which of these strategies can be implemented for their products and how well a certain design meets the requirements of these strategies. Therefore, a methodology is proposed allowing to identify feasible R-strategies that are appropriate for a specific type of product. In the next step, the methodology evaluates how the unique characteristics of a particular component allow for the application of these strategies. This methodology is applied to a case study of a vehicle door, considering and comparing the circularity readiness of various design variants. A set of specific Circularity-indicators (C-indicators) for each strategy is used for this purpose. This methodology enables comparisons among different design options, highlighting their impact on the product and material recyclability. Ultimately, the methodology helps to identify challenges in a targeted manner that guide designers in creating products that effectively support beneficial R-strategies.

Motivation & Problem Statement

In the framework of the European Green Deal the EU has triggered various legislations that require European and non-European vehicle manufacturers to strategically consider circularity requirements. For instance, the *Fit for 55* package aims to reduce the greenhouse gas emissions in the EU by 55% until 2030 with the long-term objective of achieving climate neutrality by 2050. Also, the EU has formulated the target of achieving a 25% share of domestic production for all materials according to the rules of the Critical Raw Materials Act (European Union, 2024). A circular economy (CE) could significantly contribute to achieving these goals as product and material recycling tend to reduce the carbon footprints of the respective products (Ellen Macarthur Foundation) and it would also serve the circulation of materials in a closed European system. Requirements on product circularity, as exemplarily shown in Table 1 put manufacturers under pressure, as many of them can only be realized with strategic decisions (Hansen et al., 2024). Strategic partnerships must be established to secure access to recycled materials, for example. Other maxims, such as meeting recycling quotas or ensuring the required dismantling of components (such as requirements E4.1-E7), can only be achieved with a focus on design for recycling. To fulfill these requirements, the automotive industry's access to recycled materials must be drastically improved. This can only be achieved if, in addition to mechanical recycling, other recycling options such as chemical recycling are introduced and scaled up to industrial scale. Further requirements, which, for example, promote a design that is suitable for dismantling (E7, C28) or demand implementations of CE measures for vehicles at a more strategic level (E9) will follow.

However, these targets can only be achieved through the consistent application of CE measures and strategies across a product's entire life cycle which implies a consideration in product development already.

Law	Art.	Circular Economy Requirement
E	4.1	At least 85% of end-of-life vehicles are recyclable and 95% are recoverable
E	4.2	Collecting the necessary (material) data from the entire supply chain to determine recyclability and recoverability
E	6.1	Compliance with the recyclate content: Plastic must consist of at least 25% by weight of recycled plastic, 25% of which must be from end-of-life vehicles
E	6.2	Review of minimum recycled content for steel, aluminium, magnesium and rare earths to be followed by implementing acts
E	7	Construction of vehicles so that the removal of fixed components is not hindered (electric vehicle batteries, electric motors, engines, etc.)
E	9	Creation of a circularity strategy for vehicles (+ shift of responsibility to manufacturers)
E	10	Publication of the recycled content of certain (critical) materials in permanent magnets in electric drive motors, testing for aluminium, magnesium and steel
B	7	Mandatory carbon footprint declaration for batteries
B	8	Mandatory recycled content for battery manufacturing (cobalt, lithium, nickel)
C	28	Removability of neodymium magnets

Table 1. Excerpt of upcoming CE-related legislative requirements in the EU for automotive manufacturers; E: ELV Regulation; B: Battery Regulation; C: Critical Raw Materials Act; Art.: Article

In this context two classes of approaches to integrate CE requirements on product level can be distinguished. Process-based approaches, such as Life-Cycle-Assessments (LCA), apply modeling of end-of-life processes, which includes disassembly or mechanical recycling. The results allow to assess different product designs based on performance values. Criteria-based approaches, on the other hand, use predefined criteria to evaluate product designs (Kroll & Hanft, 1998; Roithner et al., 2022). These are for example the numbers of different materials or joining techniques used. However, existing criteria-based approaches that aim to integrate CE-requirements into product development through the application of indicators seem to over simplify the problem. These do not specifically evaluate the general applicability of R-strategies to a specific product type and thus do not assess the circularity readiness in a targeted manner. Further they often seem to only focus on one or two of the R-strategies exclusively and can thus not provide a full picture.
Against this background, the paper presents a methodology that helps product developers integrate circularity requirements into product design and management. It enables comparisons between different design options, emphasizing their effects on product and material recyclability. The remainder of this paper is structured as follows: The upcoming section presents the theoretical foundations and the current state of research on supporting CE-compliant product development, from which the research questions are derived. Following that, a methodology is introduced to incorporate circularity readiness into product development. The methodology is then applied to the example of a vehicle door in the subsequent section.

Theoretical Foundations & State of Research

This section firstly presents the overall concept of circular economy and then highlights the current research state on its integration into product development.
As explained in the introduction, there are process and criteria-based methodologies and approaches to assess the circularity of product design. For this analysis we only focus on the latter. These generally have the advantage of being more straightforward in their application but deliver less exact results.

The Concept of Circular Economy

The 9R framework consists of nine hierarchically organized strategies designed to promote CE principles, focusing on resource efficiency and sustainability. The hierarchy is based on the contribution each individual strategy could potentially have in fostering a CE (European Union, 2017). The strategies are ranked as follows: Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. By following this hierarchy, companies can minimize waste, reduce environmental impact, and create value from resources throughout their life cycle, prioritizing the most effective strategies first.
In general, the CE describes an "economic system that replaces the end of life (EoL) concept with reducing, alternatively reusing,

recycling, and recovering materials in production/distribution and consumption processes" (Kirchherr et al., 2017).
The transition to a CE can only succeed by applying the circular practices at all system-levels from micro (e.g. product), meso (e.g. eco industrial park) to macro (e.g. city, country). A detailed explanation of the established CE-levels refer to Kirchherr et al. (2017). Current studies on the evaluation of circular product performance on micro level using C-indicators emphasize that many approaches do not fully capture the complexity of the levels scope (Roos Lindgreen et al., 2020). Therefore, Saidani et al. (2017) propose the nano level as an extension, focusing on the circularity of products, components, and materials across the life cycle. Within this context, a C-indicator can be defined to measure the extent to which a product or system aligns with practices and strategies aimed at advancing a CE. Higher circularity indicates that a product or system is closer to achieving the objectives established by the guiding principles of CE (Oliveira et al., 2021).

Research on Methods for integrating Circular Economy Principals into Product Development
To integrate the R-strategies into the product development process and to handle the expanded solution space due to the integration of the CE perspective, intensive research is being conducted on methods and tools in the context of circular product design.
The Circular Pathfinder is a tool developed to support companies select appropriate circular design strategies. Developed from original equipment manufacturer (OEM) case studies, it emphasizes ease of use and fills the gap in industry-driven tool development for circular and sustainable design. The software guides users through product-related questions and suggest suitable design strategies with practical examples. However, an evaluation of the tool found that its emphasis on usability overly simplifies the complexity of strategic design decisions (van Dam et al., 2017).
Aher et al. (2023) highlight the growing application of C-indicators in design processes, often assuming extensive design changes (e.g., material substitutions, end-of-life treatments) that may overlook trade-offs between indicators, technical performance and design feasibility. A simulation-based method is introduced that links design attributes and C-indicators to evaluate the impact on circularity and technological constraints, such as stiffness. The framework builds on the insights that micro level indicators generally comprise energy, mass and time terms, which can be estimated using commonly applied models (e.g., CAD, FEA) during the product development process.
Similar challenges are pointed out by Ortner et al. (2022) and Turke et al. (2024), noting that existing methods in circular product design often face difficulties in identifying the best solutions from numerous variants and to manage multiple, potentially conflicting or redundant CE objectives. To address these challenges, they propose a multi-objective optimization procedure exemplified through the integration of C-indicators.

Research on Metrics for the Circular Economy
Apart from integrating C-indicators into design methodologies, research is advancing the development of new CE measures. Recent review papers have examined the current state of metrics in the CE. For instance, a structured identification of indicators that aim to assess and monitor CE performance of products and companies is proposed by Saidani et al. (2019). The authors identified 55 different sets of C-indicators, which have been categorized in a newly developed taxonomy to facilitate their appropriate application and to highlight challenges in industry implementation.
Pascale et al. (2021) reviewed C-indicators across the established levels (macro, meso, micro) to evaluate their effectiveness in supporting the establishment of a CE. The study highlights that while indicators are valuable for supporting circularity, there is no standardized metric for measuring a CE. This lack of standardization poses a significant challenge to the consistent assessment of progress toward CE aspirations.
The research by Oliveira et al. (2021) presents a comprehensive review focused on nano and micro level indicators, evaluating them based on their relevance to sustainability pillars and life cycle stages (take, make, use, recover). The objective is to support decision-makers in selecting the most suitable indicators for circularity assessments.
Shevchenko et al. (2024) reviewed 544 articles to provide an inclusive research landscape.
By clustering recent publications with a focus on C-indicator-driven tools, four key areas were identified: "C-metrics-based tools for circularity assessment", "circular design-intended tools

built on C-metrics", "C-metrics-based tools for monitoring the process" and "database-related built on C-metrics". This leads to a research agenda comprising seven key challenges. These include, for example, the "lack of standardized design toolkits based on robust C-metrics that facilitate data-driven decision-making for developers, engineers, and designers in the early stages of product development".
In summary, the literature review identifies several major research needs. Firstly, for a given product category it needs to be identifiable which R-strategies actually make sense to apply. Secondly, when R-strategies have been identified, it needs to be evaluated to what extent a given product is able to fulfill the requirements that these strategies entail. Therefore, a set of different indicators exists (e.g., recycled content, product carbon footprint) that need to be combined to provide a holistic picture of a given case.

Methodology

As explained in the introduction automotive manufacturers are obligated to incorporate CE-Strategies on micro level. Therefore, they need to evaluate which of the R-strategies are applicable to their products and to what extent a specific product design meets the requirements of these strategies. To strategically address CE requirements, the procedure illustrated in Figure 1 is proposed. The main novelty lies in its dual-perspective evaluation of R-strategies applicability. Firstly, a qualitative assessment determines which R-strategies are applicable for a certain product type. Secondly, the focus needs to be how the R-strategies can be applied to a product regarding its specific characteristics. The overall procedure consists of six steps. The product for which CE strategy is to be applied must be specified. This pre-selection is crucial because the applicability of different strategies depends on the individual use. In the second step, the R-strategies are selected. This selection is guided by a questionnaire (annex) containing specific questions to determine whether the strategies are applicable to the object in question. Applying remanufacturing, for example, requires a demand for the product after its first use stage in a similar form with comparable characteristics and specifications. Subsequently, the CE level (nano, micro, meso or macro) for which challenges and enablers are to be determined needs to be selected. As discussed previously the challenges vary significantly depending on the perspective. These may include managing policies at the macro level, supply chains at the meso level or concern product design (micro/nano level).

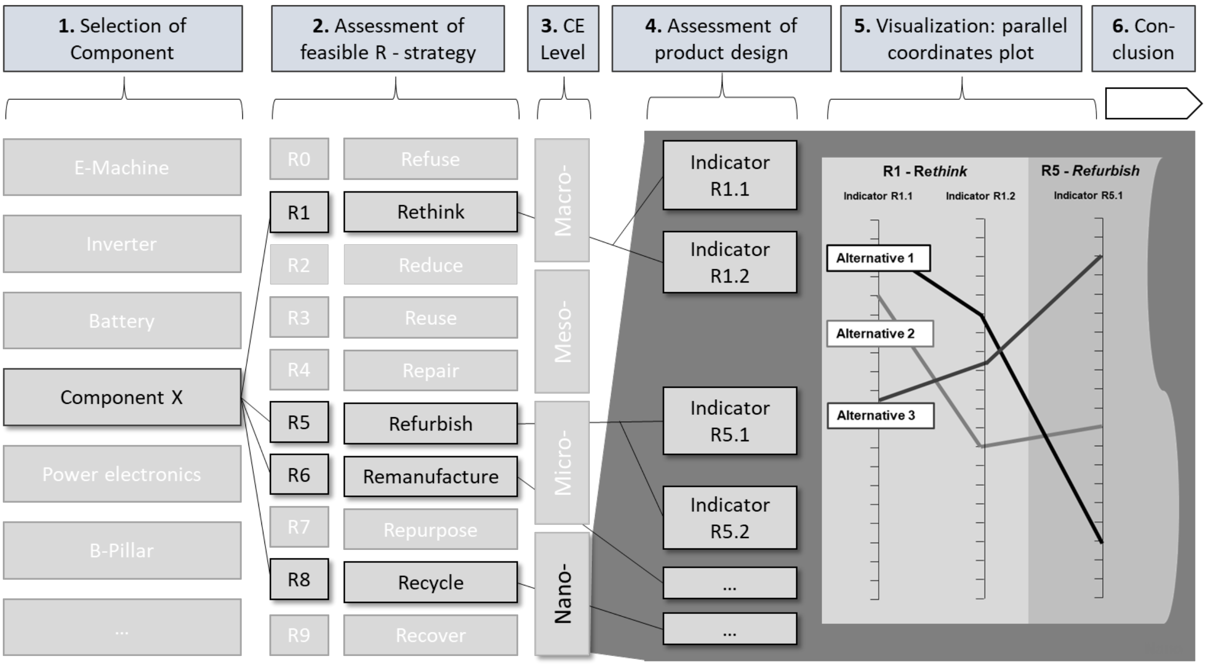

Figure 1. Methodology to derive R-Strategies for component types and evaluate their applicability for a specific product or component taking into account its specific characteristics

In the fourth step, R-strategy specific indicators are applied to assess the reference object in detail. These indicators help determine the extent to which the selected R-strategies are applicable to the object in its current conditions. Additionally, they enable comparisons with objects of the same kind, thus facilitating benchmarking. An excerpt of possible indicators that were extracted on the basis of the literature research is presented in the following section when applying the method and will be expanded in future work. The results of the quantification are visualized using a parallel coordinates plot, which enables a comparison of the different concepts. In the final step, the performance of the concept variants is compared to the best-performing solutions in terms of circularity, to identify the most critical challenges that need to be addressed.

Exemplary Application

In the following, the methodology presented in the previous section is applied to a case study.

Selection of the Component and feasible R-Strategies

The methodology starts with the selection of the component to be evaluated with regard to its circularity readiness. Within the case study a vehicle door is used. Table 2 shows the main characteristics of the vehicle door that is used as reference design. The data does not refer to an actual product but serves solely as an illustrative example to showcase the introduced methodology. To analyze different design decisions material substitutions are made to the door panel and window frame components, using steel and aluminum as alternative materials. In addition, the share of recycled plastic in the interior lock component is varied. Based on these design changes, two further concepts are derived, to which relevant and suitable indicators are applied (annex Table 5 and Table 6). Their key figures are then compared to evaluate the individual performance and trade-offs. Concept 1, the lightweight design concept, is characterized by a significantly higher proportion of aluminium, both in comparison to the reference design and to Concept 2. In contrast, Concept 2 is characterized by the highest proportion of recycled plastic for the interior lock among the designs.

In accordance with the first step of the methodology, the several R-strategy specific questions provided in annex (Table 4) were answered for the case study. The results indicate that the strategies reduce and recycling are applicable for the considered component among others.

Automotive vehicle door

Further characteristics

- Fictitious example based on research car body
- Steel door (reference)
- Total weight: 40kg
- Applicable for personal vehicles

Component	Composition/Alloy	Mass (kg)
Door Panel	Iron	19.9
	Carbon	0.1
Door Trim	Acrylonitrile	1.5
	Butadiene	1
	Styrene	2.5
	Impact Modifiers	0.6
	Heat Stabilizers	0.4
Window Frame	Aluminum	3.8
	Silicon	0.1
	Magnesium	0.1
Window	Soda-lime glass	3.5
	Polyvinyl butyral (PVB)	0.5
Seal	Ethylene	0.8
	Propylene	0.7
	Diene Monomer	0.4
	Processing Aids	0.1
Hinges	Iron	1.96
	Carbon	0.04
Window Regulator Mechanism	PA66 (Polyamide 66)	0.8
	Glass Fiber	0.1
	Impact Modifiers	0.1
Interior Lock	Polypropylene	0.8
	UV Stabilizers	0.1
	Colorants	0.1
Total Weight		**40 kg**

Table 2. Case study: Bill of materials of steel car door and its main characteristics (reference design). Image taken from Bader, 2022

Selection of C-Indicator Application

For the selected two R-strategies, selected C-indicators are assessed to evaluate the impact of the design decisions. The indicators are listed in Table 3 and have been derived from the presented state of research and will be explained in more detail below. These indicators represent a preliminary selection and are exemplary for this method. Oliveira et al. (2021) and Pascale et al. (2021) give an exemplary review of different indicators to measure circularity.

R-Strategy	C-Indicator	Description	Reference
Reduce	Mass fraction	Evaluation of reduced mass	-
	Material Carbon Footprint	Environmental impact through material selection	Federal Office for Economic Affairs and Export Control (2024)
	Production Waste (Wcp)	Waste from component production	Bracquené et al. (2020)
Recycle	Statistical Entropy (SE)	Evaluation of the material mixture	Roithner et al. (2022)
	Circular Economy Indicator	Comparison of tensile strength	Jamnongkan et al. (2022)

Table 3. Applied C-indicators to identify R-strategy readiness of a specific component or product

For the R2 strategy (reduce) three C-indicators are considered, namely mass fraction, carbon footprint and a waste production indicator (W_{cp}). The mass fraction evaluates the reduction in component mass compared to the mass of the reference design resulting from a design modification. In combination, the carbon footprint of material, expressed in tons of CO_2-equivalent (CO_2-eq), is utilized to assess the environmental impact of the selected material (BAFA, 2024). Additionally, the production waste indicator exemplarily representing the efficiency of the manufacturing process within this case study. This indicator is part of the Production Circularity Index (PCI) (Bracquené et al., 2020), and it assesses manufacturing efficiencies based on literature values for global production. This selection of C-indicators allows for an exemplary evaluation of the impact of design updates in the reduce context across the life cycle stages (Take, Make, Use, Recover).

For the R8 strategy (recycling), two C-indicators are applied as examples. The first is the product inherent recyclability index (RPR) as applied in Roithner et al. (2022) and the second is the Circular Economy Index (CEI).
The RPR evaluates the recyclability based on the statistical entropy (SE) of a product, which reflects the complexity of the material mixture. The more materials are used and the more evenly these are distributed, the worse the evaluation result.

The CEI represents a characteristic value where a recycled EoL product is set in relation to the value of a newly manufactured product. This approach offers the advantage of considering the recyclate quality without necessitating the conduction of a complex life cycle assessment (even though it cannot replace it). The value of the material can be determined by the monetary value, but also by a chemical or mechanical characteristic value (Di Maio & Rem, 2015). In this example, the value is simplified by using the mechanical quality, represented by tensile strength. The required quality is determined based on the tensile strength of the virgin material. According to studies by Jamnongkan et al. (2022), which measured a loss of 9% in tensile strength for polypropylene samples with 20 wt% recycled content (rPP20) and 12% for 40 wt% recycled content (rPP40), this can be assumed for the quality of the recycled material.
Figure 2 illustrates the results of the assessment performed in this study. The indicators are organized according to the R-strategy they evaluate. To ensure consistency, the scales of the indicators associated with the Reduce strategy are inverted, such that an upward trend reflects a positive outcome. Furthermore, all results are normalized relative to the indicator values of the reference design.
The Figure demonstrates how a design decision impacts multiple aspects of the R-strategies.
For example, the analysis of Concept 1 highlights that a material substitution results in a mass reduction but it also increases waste in the manufacturing process of the material. Simultaneously, this design decision reduces the intensity in the material mix, enhancing recyclability as reflected by the indicator RPR.
In summary, the developed approach enables the identification of potential trade-offs, both between different R-strategies and within individual ones.

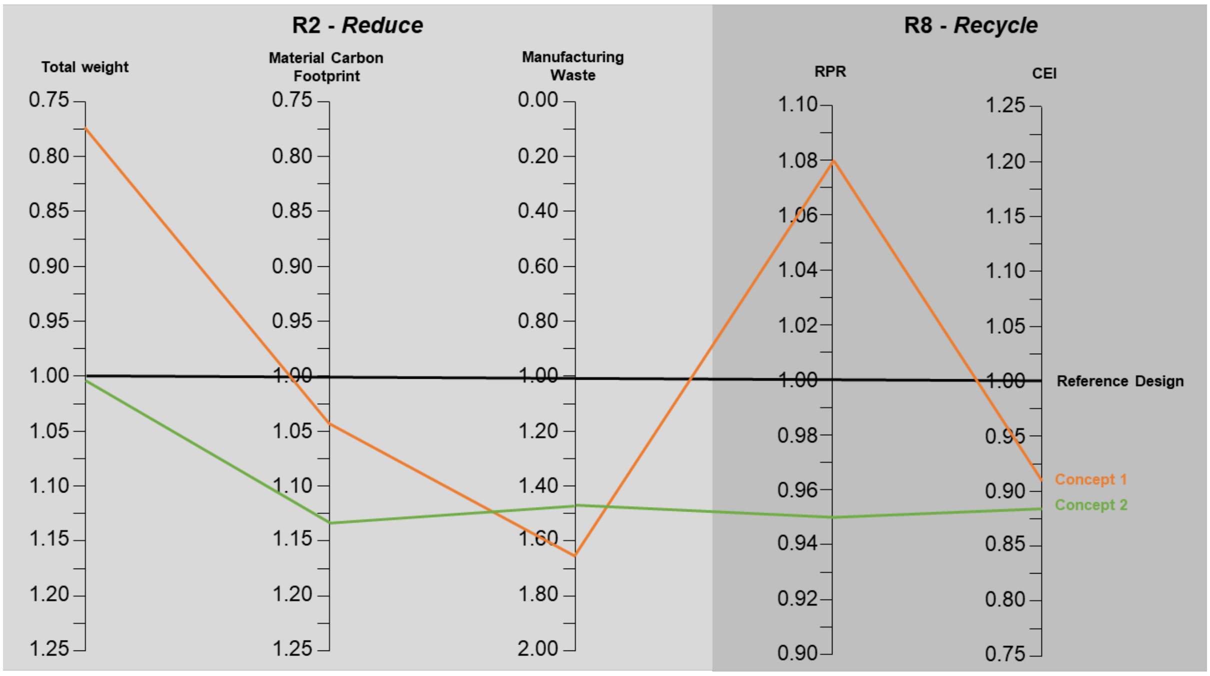

Figure 2. Results of the single indicators that have been applied to the reference design and the concept variants. The underlying results have been normalized, with the reference design assigned a baseline value of 1.00

Conclusion and Outlook

This work introduces a methodology for identifying and evaluating relevant R-strategies a given product to advance circular product design. Key contributions include a structured approach to derive potentially applicable strategies for certain product types and the identification application of suitable of C-indicators to assess to what extent the relevant strategies can actually be applied to a specific product design. Based on that, the developed approach allows for the identification of challenges that limit the strategies' practical implementation.

The developed methodology is exemplarily applied to a vehicle door on the nano level of CE. For this case study essential strategies from the 9R framework are identified. Subsequently, key characteristics of the vehicle door are changed. The results demonstrate that these changes significantly influence the applicability of the R-strategies, providing valuable insights to support decisions for a 9R-strategy-compliant design.

The C-indicators applied in the assessment were chosen to represent the applicability of the R-Strategies. However, within the scope of this contribution, only a selection of these indicators could be presented. In practice, 9R strategy-compliant design decisions are much more complex to make, which is why the examples shown here do not do justice to the complexity of the topic. This highlights the need for further development of the presented indicators and the inclusion of additional indicators to create a more comprehensive evaluation framework.

One example of an indicator requiring further refinement is the assessment of recyclability based on the statistical entropy of a material composition. While this approach accounts for the mixing of different materials, it remains independent of the specific materials used. Consequently, it cannot evaluate the extent to which the materials in a component can be effectively separated during a recycling process.

The use of recycled materials or material substitutions, as demonstrated in the case study, often demands design changes to maintain technological requirements e.g., the stiffness, strength, or dynamic behavior of the component. However, the indicators considered within this framework for the R2-strategy (reduce) do not provide insights into the mechanical properties of the component.

Furthermore, accurately assessing the material properties of recyclates is crucial for achieving EU targets for the integration of recycled materials in automotive manufacturing and advancing the circular economy.

The utilization of artificial intelligence (AI) as a methodological tool in this context presents a promising approach. This highlights the need to identify additional indicators that are more relevant and suitable for integration into the framework. Such design changes typically require computationally intensive and time-consuming structural analyses of the component. AI could also be brought into the product development and computational optimization process as it could provide a solution to these challenges. AI can potentially not only reduce computation time but also improve optimization outcomes. In addition, it can be used in the optimization process to resolve possible conflicting objectives of the R-strategies and to carry out design optimizations with sustainability and circularity requirements. Based on the evaluation, suitable Design for X (DfX) guidelines can be proposed, such as strategies to reduce mass through lightweight design or improve recyclability through modularization. Integrating these guidelines directly into CAD programs enhances acceptance and availability by enabling real-time tracking and evaluation of design decisions. This supports sustainable design choices while maintaining mechanical properties and technical performance.

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Annex

Strategy	Questions on product type	Y/N
R2: Reduce	Can a material that significantly contributes to the total weight of the *c/p* be substituted with a lighter one?	
	Is it expected that significant amounts of material can be saved by applying methods and tools of lightweight design (e.g., shape optimization)?	
R3: Reuse	Can *p*-life be expected to be longer than the initial use phase without further intervention?	
	Can the service life of *c* be expected to exceed that of the entire product without further intervention?	
R4: Repair	Can the *p/c* be expected to be subject to wear and tear during its lifetime?	
	Is the lifetime of the entire *p* likely to exceed that of the *c*?	
R5: Refur-bish	Is it to be expected that a further utilisation phase for the *p/c* can be realised through targeted interventions?	
	Can the *p/c* also be used sensibly in a state below new condition?	
R6: Remanu-facture	Is it to be expected that a further utilisation phase for the *p/c* can be realised through targeted interventions?	
	Is there a need for the *p/c* beyond the first phase of use?	
R7: Repur-pose	Can the *p/c* be used sensibly in another application after the first use phase?	
R8: Recycle	(none)	
R9: Recover	Is it not possible to recycle *p/c* under any circumstances?	

Table 4. Excerpt of a possible questionnaire of R-strategy specific questions to identify which strategies are eligible for a certain general product (p) or component (c) type

Concept 1

Component	Composition/Alloy	Mass (kg)
Door Panel	Aluminium	11,64
	Silicon	0,12
	Magnesium	0,12
Door Trim	Acrylonitrile	1,7
	Butadiene	0,5
	Styrene	2
	Impact Modifiers	0,2
	Heat Stabilizers	0,4
Window Frame	Aluminium	3,8
	Silicon	0,1
	Magnesium	0,1
Window	Soda-lime glass	3,5
	Polyvinyl butyral (PVB)	0,5
Seal	Ethylene	0,8
	Propylene	0,7
	Diene Monomer	0,4
	Processing Aids	0,1
Hinges	Iron	1,96
	Carbon	0,04
Window Regulator Mechanism	PA66 (Polyamide 66)	0,8
	Glass Fiber	0,1
	Impact Modifiers	0,1
Interior Lock	Polypropylene	0,8
	UV Stabilizers	0,1
	Colorants	0,1

*normalized to value of referenz design (basline value of 1)

Total weight*	Carbon Footprint*	Production Waste*	RPR*	CEI*
0,77	1,04	1,65	1,08	0,91

Table 5. Characteristics and calculation results for the selected C-indicators of Concept 1

Concept 2

Component	Composition/Alloy	Mass (kg)
Door Panel	Aluminium	11,64
	Silicon	0,12
	Magnesium	0,12
Door Trim	Acrylonitrile	1,5
	Butadiene	1
	Styrene	2,5
	Impact Modifiers	0,6
	Heat Stabilizers	0,4
Window Frame	Iron	6,08
	Carbon	0,32
Window	Soda-lime glass	3,5
	Polyvinyl butyral (PVB)	0,5
Seal	Ethylene	0,8
	Propylene	0,7
	Diene Monomer	0,4
	Processing Aids	0,1
Hinges	Iron	1,96
	Carbon	0,04
Window Regulator Mechanism	PA66 (Polyamide 66)	0,8
	Glass Fiber	0,1
	Impact Modifiers	0,1
Interior Lock	Polypropylene	0,8
	UV Stabilizers	0,1
	Colorants	0,1

*normalized to value of referenz design (basline value of 1)

Total weight*	Carbon Footprint*	Production Waste*	RPR*	CEI*
0,86	1,13	1,47	0,95	0,88

Table 6. Characteristics and calculation results for the selected C-indicators of Concept 2