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Review

A critical review of the current state of circular economy in the automotive sector

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ABSTRACT

A circular economy (CE) offers, compared to a linear economy, various strategies to reduce consumption and demand of natural resources as well as additional secondary benefits that serve to achieve sustainability goals. However, the extent to which these goals can actually be achieved depends on the quality of the strategies used in terms of circularity. Against this background, this work examines the current understanding of the term circularity in the automotive sector. With the help of a literature review based on available publications in the period 2012–2021, a hitherto missing overview of circular strategies used in the automotive industry is given and compared with the political claims. Furthermore, current research activities are evaluated. The evaluation process is carried out by a classification into different cycle concepts, the so-called R-strategies, where avoidance and reuse are seen as the optimum. Existing R-strategy-concepts from literature were adapted and expanded. It becomes clear that both industry and research in majority equate the circularity of a product with (inferior) recyclability. High-quality CE strategies for reuse and further use as a substitute for new production, which already have to start in the product development phase, do not exist in the industry and are also strongly underrepresented in research activities. A large gap is revealed between the goals of a CE, which are accordingly on the political agenda of many states, and the implementation in industry. The aim of this review is to use the status quo for highlighting the need for action to promote higher-quality circular methods, which favour sustainable economy.

1. Introduction

By 2060, the world population is expected to increase to almost 10 billion people (UN DESA (Population Division)). At the same time, it can be assumed that the share of the global middle class will rise (HKEx-news), which is likely to result in a strong increase in product demand in the automotive sector, especially in the emerging countries. Due to these developments and, furthermore, the transformation of the automotive sector from conventional to new drive train technologies contributes to a high demand for non-renewable resources, e.g. so-called critical minerals (IEA).

The transition from an unsustainable linear "throw-away economy" (Frosch and Gallopoulos, 1989) to a circular economy (CE) is seen as a possible answer to these developments (Arnold et al., 2023) and recently gets a lot of attention (Geissdoerfer et al., 2017). The principles of a CE offer promising approaches to counter the problems of resource scarcity and price increases, minimise waste, as well as to reduce energy input and pollutant emissions necessary for new production (Geissdoerfer et al., 2020). A strengthening of local production in relation with reduced logistic costs and economical independence are further benefits. However, there are great challenges, for instance quality issues due to material connections, wear and contamination through use, high setup and process costs or supply chain complexity (Arnold, 2023), (Greer et al., 2021). But if it is possible to operationalise these challenges, a high circularity level has the potential for contributing to a sustainable

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Abbreviations

CE	circular economy
EoL	end of life
ELV	end of life vehicle
EU	European Union
LC	life cycle
LCA	life cycle assessment
OEM	original equipment manufacturer
PEP	product engineering process
(9)R	(9) circular strategies
R&D	research and development
SDG	sustainable development goals
UN	United Nations
WoS	Web of Science (database)

and profitable (automotive) manufacturing industry while decoupling from the negative consequences of resource depletion and environmental degradation (Morseletto, 2020), (Murray et al., 2017) and with a decisive reduce of carbon emissions and non-renewable resource consumption, e.g. by up to 75% resp. 80% per passenger kilometre for battery electric vehicles (Accenture).

Due to the high complementarity with sustainability, the concept of the circular economy has increasingly found its way into the political agendas (Brennan et al., 2015), (Herrador et al., 2022). This is evident, for example, in the EU Action Plan (European Commission), the Circular Economy Vision 2020 of the Japanese Ministry of Economy, Trade and Industry (Ministry of Economy and Trade and Industry, 2020) or in China's Circular Economy Promotion Law (Lieder and Rashid, 2016). CE has also received increasing attention in academia over the last two decades, with a wide range of reports on the subject in different manufacturing sectors, e.g. Andersen (2007), Ghisellini et al. (Federal Ministry for the Environment, 2012), Su et al. (2013) of Acerbi and Taisch (2020). Specific areas of attention are closed loop value and supply chains, e.g. (Govindan et al., 2015), circular business models (Hofmann, 2019) and circular product design (Stavropoulos et al., 2019). However, the review of Lieder and Rashid (2016) highlights that research on CE often lacks concrete examples of newly designed or manufactured products that enable closed-loop systems. Sonar et al. (2022) also identified the design as a barrier to CE. Maldonado-Guzmán et al. (Maldonado-Guzmá et al., 2021) emphasized the need for further research on eco-innovation at the product, technology, process, management and marketing levels.

Automobile OEMs have also recognised the advantages of CE and begun to incorporate them into corporate strategies in a promotionally effective way. The review by Valladares Montemayor and Chanda (Valladares Montemayor and Chanda, 2023) provides a detailed overview of the current status of the CE for the 10 largest car manufacturers worldwide with regard to applied CE principles and the potential of their implementation against the background of the transformation from the combustion engine to the electric drive. The authors stress that current efforts are not scalable and hardly any aspect of the vehicle outside the powertrain, fuel technology and recycling were considered. However, this review represents the manufacturer's view by using only corresponding sources. The consideration of academic sources is missing here, and the focus is clearly on EV. Further reviews in the automotive CE context focus on end-of-life (EoL) management. Karagoz et al. (2020) underscore the increasing importance of end-of-life vehicle (ELV) management for environmental protection, circular economy and sustainable development due to the rapid growth of the automotive sector. The specific examination of Industry 4.0 approaches in EoL management is for instance content of Poschmann et al. (2020). Tarrar et al. (2021) highlight the gap between scientific knowledge and practical industry needs in improving ELV management, particularly in vehicle dismantling. Other works focus on recycling and recovery processes of specific materials or specifically address the recycling of electric vehicles or lithium-ion batteries (D'Adamo and Rosa, 2019), (Islam and Iyer-Raniga, 2022). Regarding other approaches beyond recycling, there are fewer studies available. One study explores remanufacturing and refurbishment as strategies for life extension in various industries (Ferreira et al., 2021). Only de Kwant et al. (de Kwant et al., 2021) examine the challenges faced by manufacturers in implementing circular principles in product design.

Against this background, and to fill the gap that there is hardly any work dealing with a comprehensive spectrum of circular economy principles in the automotive sector, this paper has compiled a literature review that provides an overview of current R&D activities in the field of automotive CE. As an example, for relevant legislation, the "new Circular Economy Action Plan" (European Commission), announced by the EU Commission in 2020, indicates that there is already an agreement at the political level on the advantages of a CE and what they look like. The aim of this paper is to show to what extent the ideas of the CE have so far been implemented in concrete concepts or even examples of application in the automotive sector. In this context, it can also be shown how measures to increase circularity are implemented by the various stakeholders or how the attribute circularity is understood at all. On the one hand, this should show how far (socio-political) aspirations and (industrial) reality currently lie apart. On the other hand, it may also be possible to identify potential obstacles to implementation. Ultimately, this should provide a basis for further research activities to develop approaches for resolving the conflict between the three factors that are essential for modern product development: economic efficiency, functionality and sustainability (through circularity!) for reaching the previous mentioned benefits.

For reducing the scope of the research to a manageable quantity, the limiting focus is on the consideration of motor car chassis, as one of the most important assemblies in the vehicle besides the drive train. Approximately 20% of the costs and 25% of the weight of today's passenger cars are caused by the chassis (Ersoy and Giess, 2017). The wide number of tasks in connection with countless electronic control systems results in a high level of complexity and many different materials. Nevertheless, the chassis is largely invisible to the customer. Therefore, it offers itself to implement a functioning circularity and e.g. reuse chassis components several times, after reconditioning.

In the following section 2, CE principles are explained and an evaluation scheme for the quality of CE strategies, so called R-framework, is presented, before the methodical procedure of the literature research is presented together with the definition of the research questions in section 3. This is followed by the evaluation and discussion of the review results in sections 4 and 5.

2. Circular economy principles

The principles of a circular economy refer to a form of production and use in which existing products or their components and materials contained are used as long or intensively as possible (Al-Swidi et al., 2023), (Moreau et al., 2017). In practical terms, this means that products are designed to be functional and durable, are used intensively, shared or leased, and product components are reused, repaired, refurbished or recycled (European Parlament). In this way, utilization and service life are increased on the one hand, and on the other hand the subcomponents are retained as far as possible for value creation even after the end of the product's life. This results in changed requirements for design and manufacturing processes, whereby the entire product life cycle should be designed in the sense of a sustainable CE (Götze et al., 2019), (Korhonen et al., 2018). This means that product development, starting with the extraction of raw materials right through to production, should be designed to avoid or reduce the use of natural resources. The finished product should also be formed in such a way that it can be used for a long time and intensively, while at the same time being environmentally friendly and resource-saving. For this purpose, easy reparability and reprocessing should already be considered in the design process. In terms of a closed-loop system, the requirements for a product result not only from the production and usage time, but also from the changed handling of the product or its components after the primary life cycle (Ellenmacarthurfoundation, 2023), (Korhonen et al., 2018).

Germany was a pioneer in adopting the CE into national laws with the enactment of the “Closed Substance Cycle and Waste Management Act” in 1996 (reorganised in 2012 as “Circular Economy Act” (Su et al., 2013)). Japan has followed in 2005 with a “Basic Law for Establishing a Recycling-Based Society” (Zhang and Chen, 2014) and China 2009 with the “Circular Economy Promotion Law of the People’s Republic of China” (Lieder and Rashid, 2016). Most notably supranational law is the EU’s 2015 Circular Economy Strategy (Geissdoerfer et al., 2017) extended by the EU action plan (European Commission). According to the EU Waste Framework Directive (European Union) the reuse or further use of a used product is pursued as the ideal. If this cannot be realised, the recovery of materials and valuable substances for a comparable (recycling) or a qualitatively inferior application (downcycling) are possible subsequent stages. Purely energetic recovery should be avoided wherever possible, following the principles of a circular economy, or should be regarded as the last means of avoiding waste (landfilling) as the lowest hierarchical level of EoL treatment (compare Fig. 1).

2.1. Waste hierarchy

In countries with ELV legislation, this hierarchy often forms the basis for dealing with ELV in the form of quantitative recycling and recovery quotas, for example in Germany (Bundesamt der Justiz), UK (Environment Agency, 2021), Japan and South Korea (Jamaluddin et al., 2022). Energy recovery and recycling of materials and substances are comparatively simple forms of recovering and are therefore the preferred methods in the automotive sector for meeting these legal quotas (Kohlmeyer, 2022). From a circular economy perspective, however, these forms of ELV treatment must be viewed critically. The two lowest levels of the EoL hierarchy shown – disposal and energy recovery - do not represent measures of a closed-loop system, as resources treated in this way are irretrievably destroyed. Therefore, they are no longer part of the intended material cycle. In recycling, too, a distinction must be made as to what the recycled material can subsequently be used for. The use for the same (or even higher) application purpose already poses considerable requirements compared to downcycling and should already be considered in the product development process (PEP). Functional reuse in a new product or reuse in a comparable product is the highest form of resource reusability. According to §2 of the German End-of-Life Vehicles directive (Bundesamt der Justiz) the term (functional) reuse is defined as follows: “Measures in which end-of-life vehicle components are used for the same purpose for which they were designed.” In this form, natural resource consumption cannot only be decreased (ideally to zero), but the energy input for production and logistics is also eliminated or significantly reduced.

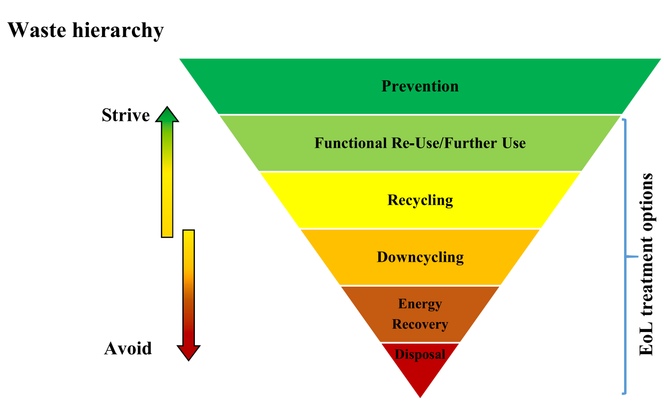

Fig. 1. EoL-Treatment in accordance with the waste hierarchy (European Union).

Assuming a necessary and existing product (prevention is thus ruled out), the authors see a product design for reuse as the key factor to reach the goals of CE. This leads to the central research question of this review:

How are the key objectives of a circular economy, in particular direct reuse and concepts for further use, considered in the current automotive product engineering process?

By analysing the literature found, the research questions derived in the next section should provide insights to answer this central question in relation to the chassis assembly. As for instance shown in (Kirchherr et al., 2017), there is no uniform understanding of the CE concept. Rather, it was shown that the understanding already varies greatly in science and that numerous theoretical and practical approaches exist for the implementation of circular principles, which define the focal points of a circular product differently, from the various stages of recycling to a function-preserving reuse as the primary objective. For example, the so-called 9R-framework (Potting et al., 2017) was defined for the preservation of raw materials in a closed-loop system. Beneath the 9R-framework there exist a lot of comparable R-frameworks, that consider different numbers of Re-strategies, e.g. (Papageorgiou et al., 2021).

The “R" stands for various strategies (cf. Table 1), which are oriented towards the EoL hierarchy shown (Fig. 1) in order to increase the useful life and intensity of products and components, thereby conserving resources and avoiding waste. Based on the considerations carried out in the course of this work and the findings during the literature research, the 9R-framework (Potting et al., 2017) was critically analysed and used in the following, adapted form (Table 1) for the literature selection and categorisation. The main adaptations are the abandonment of thermal recovery (recover) and the qualitative differentiation in recycling as explained above. Other R-concepts that arose during the screening process were additionally defined and classified. The introduction and definition of the redesign strategy, which includes changed methods that already influence product creation, should be highlighted as the most significant extension. Further explanations on this subject are part of the discussion.

As a conclusion of the cited work (Kirchherr et al., 2017), the different understanding of the term was identified as a considerable risk that can cause the implementation of a CE to fail. In contrast, the aim of this review is not so much to provide a definition and/or an overview of the theoretical understanding of the CE concept, but to identify practicable solutions and challenges with the help of an overview of CE research topics and approaches to industrial implementation (sector-specific) in order to force a rethink at all levels (industry, politics, society).

3. Methods

3.1. Research questions as basis for the literature review

To answer the previous formulated main research question, the selected sources were examined according to the following aspects.

- How is the term circularity understood in the automotive sector?
- Which strategies of the circular economy are already being implemented in the automobile industry?
- In which phases of the automobile life cycle (LC) are strategies of the circular economy already being implemented and on which phases is the current research focus?
- Sustainable benefits of the CE: Which sustainable development goals (according to the 17 SDGs of UN) can be achieved (currently)?
- Which challenges/obstacles are existing for the implementation of a CE for the different stakeholders?

Table 1
Definition of advanced circular strategies based on (Potting et al., 2017).

CE-Strategies	Description	Category
R0 Refuse	Make a product redundant by abandoning its function or by offering the same function with a radically different product.	*Smarter product design, use and manufacture*
R1 Redesign	Consideration of the CE in the product engineering process, accompanied by modified processes and life cycles (Design for CE concepts).	
R2 Rethink	More intensive product use (e.g. by sharing products).	
R3 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.	
R4 Reuse	Reuse of a discarded product that is still in condition to fulfil its original function by another consumer.	*Extend lifespan of product and its parts*
R5 Repair	Repair and maintenance of defective product so it can be used with its original function during use phase.	
R6 Refurbish	Restore an old product and modernize it to fulfil current state of art.	
R7 Remanufacture	Use parts of discarded product in a new product with the same function.	
R8 Repurpose	Use discarded product or parts of it in a new product with a different function.	
R9 Retread	Displace the worn parts of a product to use it for the same function.	
R10 Recycle (Up)	Recover materials for the qualitatively equivalent (or higher) application purpose.	*Useful application of materials*
R11 Recycle Down	Recover materials for a qualitatively lower application purpose.	

In addition to these qualitative questions, which answering is fully open-ended in the course of this review, further questions are being pursued which are able to be sufficiently clarified by a quantitative evaluation of the research results.

- Who are the drivers of CE in the automotive sector: Science, industry or government?
- Where is CE applied → Which parts of the supply chain? Are there regional variances?
- Which chassis components are focused by which CE concepts?

3.2. Methodology of the literature selection

The literature search was conducted in December 2021. English-language publications worldwide from the last ten years were selected as the framework for the search, covering the topics of automotive (chassis) and circular economy. The previously described important role of the chassis suggests that the insights gained with this limiting focus also apply to other (less important) assemblies. The chassis focus was also intended to deliberately exclude articles that only specifically consider the treatment of EoL batteries of electric cars. It was known from preliminary work that these are dealing almost exclusively with recycling or further use outside the vehicle. However, the main objective of the work is to search for systemic approaches independent of isolated solutions for individual components.

The three databases TEMA®, Web of Science™ and Scopus® were used to search for relevant literature. The use of further databases could not provide any decisive quantitative added value, but only resulted in a high proportion of duplicates. The search string with the chosen keywords is shown in Table 2.

The selection process of the publications is summarised with the PRISMA approach (Page et al., 2021) in the following Fig. 2.

As the result, 4211 publications were identified. After duplicate removing, the 3339 remaining articles were subjected to a three-stage screening process based on the defined exclusion criteria (Table 3). To avoid redundancy and ensure a comprehensive synthesis of information, other literature reviews have not been included. These are based on the existing literature, which should be found anyway. This paper focuses on primary studies according to the PRISMA method to minimise possible methodological bias in other reviews, which allows for a more rigorous and unbiased synthesis. In the first step, relevance was assessed based on the titles and abstracts. The previously defined criteria led to the exclusion of 3133 publications. For the remaining 206 publications, their availability as full text was checked. Due to lack of availability, 42 publications had to be sorted out in the second step. This left 164 publications that were read in full text. The full-text analysis revealed that further works did not meet the inclusion criteria and were therefore excluded. As a result, 82 publications were included in the review. The 82 sources (listed separately in the appendix A1) are used to answer the defined research questions.

Table 2
Search string.

Domain 1		Domain 2		Domain 3
"circular economy" OR "reuse" OR upcycl* OR re-utili* OR "further utili*" OR remanufact* OR disassembl* OR dismantl* OR cradle* OR "eco design" OR recycl* OR "closed loop economy" OR "closed loop suppl*" OR retrofit OR "design for environment" OR refus* OR rethink OR refurb* OR repurpose OR recover OR r3 OR r4 OR r9 OR "second life" OR recondition OR downcycl* OR ("reduc* circular*"~255) OR ("reduc* circle"~255) OR ("repair* circular*"~255) OR ("repair* circle"~255)	**AND**	"auto" OR automobil* OR "automotive" OR car OR vehicle	**AND**	chassis OR axle OR brake OR damp* OR knuckle OR spring OR steering OR stabilizer OR stabilizer OR suspension OR tire OR wheel OR "control arm" OR "pivot bearing" OR "shock absorber" OR "top mount" OR "wishbone arm"

4. Results

4.1. Quantitative evaluation

Before answering the research questions defined in subsection 3.1 - consistent with the subheadings of this section - a brief quantitative evaluation should give an overview about the current importance of the CE in the automotive sector. The increasing importance of CE can be shown with the rising number of publications about this topic in the recent years. The following Fig. 3 compares the number of publications per year in the examined period which can be found with the data bases Web of Science and Scopus,[2] indicating the increasing relevance.

[2] The database TEMA was not available anymore at this time.

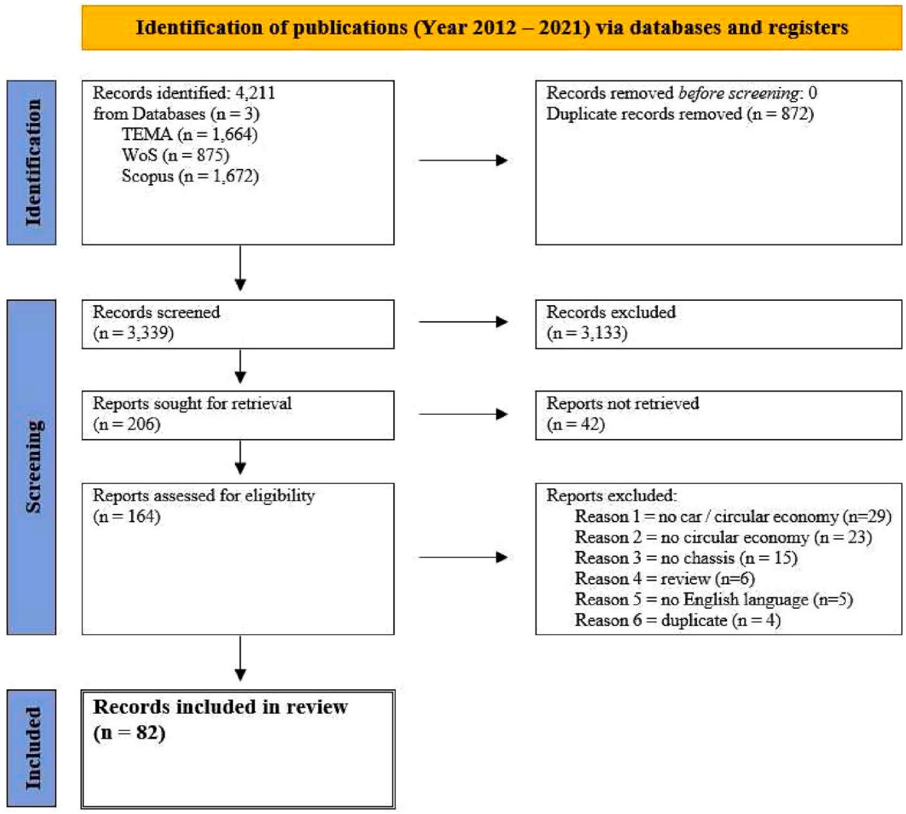

Fig. 2. PRISMA-chart.

Table 3
Defined exclusion criteria for the review process.

Exclusion criteria	
- **No circular economy**	- **Conference description**
- **No automotive**	- **Review**
- **No chassis**	- **Language**
- **No car/circular economy**	- **Wrong publication type**
- **Duplicate**	

An analysis of the publications and categorisation with the help of the R-framework showed that not all circular strategies are mentioned equally. Fig. 4 illustrates that the focus is on recycling strategies. The diagram considers that several approaches of the R-Framework can also be mentioned in one publication.

Accordingly, 45 publications (55%) refer to recycling. Notable is that the refuse strategy was not mentioned in any publication. According to the definition, refuse is the strategy that most strongly reduce the resource consumption. For example, a possible implementation of this strategy would be through functionally integrated components. The absence of the refuse concept could therefore be due to the fact since function integration and other refuse strategies are not directly associated with CE in the literature. Also, the repurpose approach was not mentioned in the publications, while remanufacturing was dealt with in 12 publications. According to the definition, the understanding of the terms remanufacturing and repurpose is close to each other, but remanufacturing corresponds better to the CE in comparison. So, it is positive that a significantly proportion of publications refer to it. However, the absent of repurpose may also be due to the structure of the search string and the formulation of the exclusion criteria, because publications in which the components are not used again directly in the chassis were excluded in the search process. Redesign approaches that take circularity into account as early as the product development phase are mentioned in 8 publications. The importance of the other strategies rethink, reuse, reduce, repair, refurbish and retread is almost equally low. At this point it becomes clear that it is reasonable to list the retreading concept separately according to the extended R-framework (see Table 1). Overall, the review makes it clear that a predominant proportion of publications deal with strategies at a lower circularity level.

An allocation of which chassis components are dealt with in the publications shows that the components brake, tyre, axle and steering are examined more intensively with regard to the recyclability (references to several components within a publication is also possible here). The following diagram (Fig. 5) shows that the tyre component is by far the most frequently mentioned (44 publications). Followed by the brake system (21 publications). This includes, for example, brake disc, brake pad, brake calliper and brake lines. The axle and steering components and the control arm were each mentioned in three publications. The category "others" includes all other chassis components mentioned, such as bearings, seals and shock absorbers, which were only mentioned once

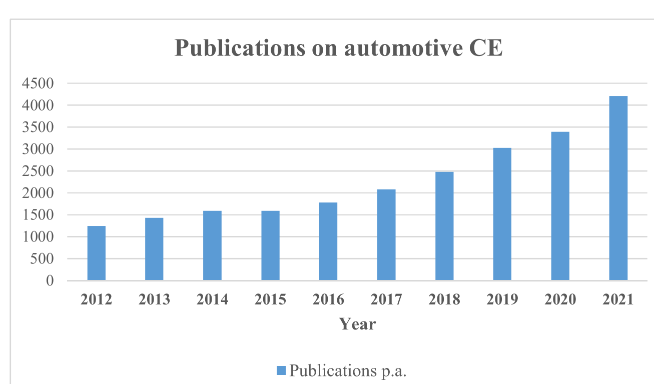

Fig. 3. Publications with the subject automotive CE 2012–2021 found with Web of Science and Scopus.

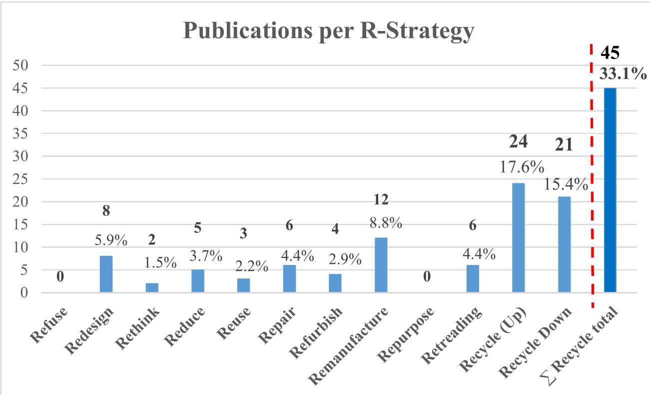

Fig. 4. Publications according to R-concept.

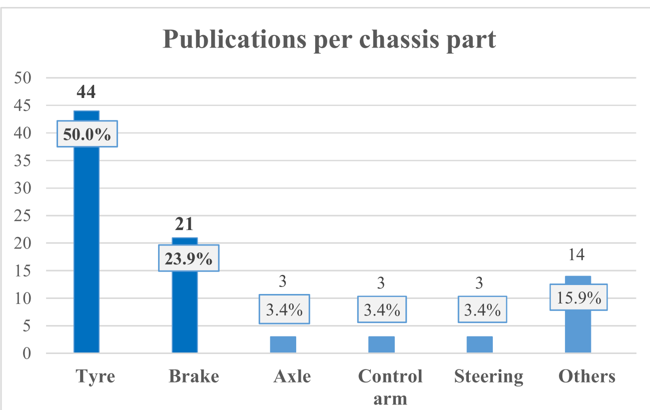

Fig. 5. Investigated chassis parts in the examined literature.

or twice.

4.2. Qualitative evaluation

4.2.1. Circularity understanding in the automotive sector

To determine how the term CE is actually understood in the automotive industry, the texts were analysed with regard to the contained methods, processes and approaches etc. and it was determined under which CE concept the authors classify them. In contrast to the quantitative evaluation (cf. Fig. 4), in which the review writers classified the analysed sources as objectively as possible according to the defined R-framework, the classification in Table 4 is now from the original authors' point of view. The reviewed literature sources are listed in a separate bibliography in the **appendix (A1)**. Only the assignment of concepts made in this table refers to this bibliography.

Again, one of the main results of this evaluation and therefore of the whole literature review is that the majority of current efforts to apply or implement CE in the automotive sector focus on recycling. As already shown in section 4.1, most of the papers deal with this concept. The more detailed analysis shows that this is almost exclusively understood as pure material recycling. The highest obvious example is the handling of EoL tyres. In most cases, a high-tech product consisting of various materials is more or less elaborately broken down into its constituent parts in order to use them as raw materials for automotive components with at best the same or lower quality requirements. Already in the first stage of the screening process, contributions were excluded in which the materials obtained in the process are no longer used in the vehicle (n = 447). This should exclude the large number of publications that deal with the use of expensive materials for a non-application purpose, e.g. as fillers for road construction. As explained in section 2, this is not to be

Table 4
CE concepts and associated strategies and methods in the reviewed literature.

CE-Concept (n = no. of appearance)	Conceptual approach (1–82 = reference number in appendix A1)
Recycling (44)	Recycling (in gen.) [a] Functional Recycling **(23, 18)**
New Method (26)	(extended) LCA **(27, 32, 38, 47, 69)** Design for CE **(2, 3, 50, 62, 65, 74, 77, 78)** Eco-Design **(21, 68, 77)** Lightweight design **(10, 16)** New Materials **(1, 21, 27, 43)** Changed Supply Chain **(52, 56, 57)** Design for Manufacturing **(66)**
Remanufacturing (20)	EoL-Management **(31, 33, 40, 38, 18, 69, 82)** Operational approach **(34, 74)** Reverse logistic **(11, 12, 18, 26, 37, 51, 56, 57)** Remanufacturing in gen. **(54, 59, 77)**
Retreading (9)	Decision Tool **(13, 47, 55, 82)** Inspection method **(8, 42, 44)** Retreading in gen. **(54, 71)**
Reuse (5)	Reuse in general **(50, 59, 82)** Refurbish for reuse **(55)** Refurbish for modernization (for further use) **(48)**
Repairing (4)	Repairing process **(36, 65, 75)** Repairing Tool **(25)**
Retrofitting (1)	Retrofitting to improve **(58)**
Recovering (1)	Energy recovering **(17)**

[a] **(4-7, 9, 12, 14-16, 19, 20, 22, 24, 28, 29, 35, 39, 41, 45, 46, 49, 50, 52, 53, 57, 60-64, 67-70, 72, 73, 75, 76, 78-81)**

seen in a sense of circular economy but only as waste avoidance. Nevertheless, the remaining articles often only deal with qualitatively lower applications, i.e. "downcycling", for example discarded tyre components as a basis for fuels, elastomers or insulation materials (cf. Fig. 4). Only two articles speak of functional recycling, which according to defined R-concepts is to be understood as remanufacturing.

The reprocessing and reuse of components and their parts for the same application (reuse, refurbish, remanufacture), which is more valuable from a circular economy point of view, is significantly less in focus. The inconsistent use and unclear separation of these terms must be noted. In various contributions, the terms retreading and retrofitting are used synonymously for these concepts, e.g. in (Reiter et al., 2020) and (Qiang et al., 2018). Again, the numerous mentioning of retreading shows the reasonability to list this concept separately. The term retreading is often associated with the treatment of old tyres by replacing worn treads with new ones, thus allowing a continued use of the tyre's basic structure. On the other hand, a clear distinction can be made with the concept of repair. This can be explained by the fact that the repair of defective product components during the use phase of the automobile is not a new concept in the CE context, to which the literature search refers. This also explains the low proportion of repair concepts in the sources examined.

The switch from a linear economy to a circular one requires a profound change in the processes involved. Correspondingly new methods are dealt with or at least mentioned in 26 contributions. The spectrum ranges from new development methods to changed supply chain management to alternative material concepts. Actual "Design for CE" concepts are mentioned in eight contributions, whereby only five ((Aziz et al., 2016), (Campana et al., 2017), (Papakostas et al., 2015), (Satu and é, 2013), (Vimal et al., 2021)) go beyond isolated solutions by presenting holistic, component-independent approaches that change processes and methods independently of the product and also take into account other influencing factors from the (whole) life cycle.

In summary, the concepts of a circular economy are mostly reduced to recycling, and this is currently used as the primary means of choice for fulfilling existing legal requirements and avoiding waste. Compared to the more complex concepts of functionally equivalent reuse, this can be justified by the relatively easy implementation combined with low implementation costs and the simultaneous generation of short-term economic advantages in the form of cheap, secondary raw materials. Accordingly, a product is already said to be circularly if a certain proportion of the materials it contains can be reused as an ingredient for a new product. However, as already explained in the introduction with reference to the ELV directives, there is no uniform awareness and no legal framework for how this reuse is to be designed.

4.2.2. CE strategies in the automobile industry

As described, recycling in the form of recovering materials from EoL products and components for further use for a similar or unrelated purpose is often used in the automotive industry. This is especially the case where there are corresponding legal provisions for the take-back and environmentally friendly disposal by the manufacturers. Independent recycling industries have formed here.

Summarised under the term remanufacturing, other strategies of the circular economy have long been used for spare parts, especially by the supplier industry. This includes all measures that serve the reprocessing of chassis parts to restore the original functional performance. According to the presented EoL-hierarchy (Fig. 1), this is definitely in the sense of a high-quality circularity. However, the main restriction here is the exclusive use of these parts for the spare parts business (Commission, 2013), (Wilde et al., 2014). A functional reuse in new vehicles that is pursued in series production is not documented by the database. For the aftermarket, however, remanufactured parts are offered at a discount compared to new parts.

Recovering, i.e. the use of EoL products for energy generation through incineration, was actually excluded in the course of the literature selection. Nevertheless, it should be explicitly mentioned here as an essential measure used to avoid waste, as it also appears in the remaining literature in connection with other R-concepts (see Table 4). Energy recovering is necessary or applied wherever functioning structures for recycling and reprocessing on an industrial scale are lacking.

4.2.3. Focussed phases of the automobile lifecycle

The main focus of the activities described above is on the handling of ELV respectively EoL chassis components. It can thus be stated that currently implemented circular approaches largely refer to the end of product life (Fig. 6). There are only a few examples from industry that already include the circular economy in the design phase in the form of design for remanufacturing. Here, the focus is usually on easy dismantling, i.e. (Satu and é, 2013).

Most research work also only starts in the EoL phase. In contrast to the strategies implemented in industry, however, the design and use phases are low increasingly coming into focus of research activities. The most detailed consideration here is energy and cost savings by using secondary raw materials from recycling for new production in the context of LCA (Gradin et al., 2020), (Karakoyun et al., 2014), (Ounsaneha et al., 2020), (Torretta et al., 2015). The production phase is addressed with questions about logistic, e.g. (Pereira et al., 2018) and supply chain management, e.g. (Cheraghalipour et al., 2017), with a marginally connection to the CE. The fact that CE strategies such as the R-concepts and beyond are already fully incorporated in the design process is thus not the case in the automotive industry, and such examples are also rare in research (9%).

4.2.4. Relations of CE and sustainable development goals

As enshrined, among others, in the EU Action Plan (European Commission), CE strategies and the renunciation from the linear economy are seen at the international political level as essential factors for sustainable economic activity. To examine the connection between CE and sustainability, the sources were analysed based on the UN's Sustainable Development Goals ("17 SDGs", cf. (UN Department of Economic and Social Affairs, 2023)).

Both the direct and the contextual reference to these goals were counted, whereby multiple naming was possible, as a clear separation could not always be made. For example, there were numerous overlaps within SDG 12. Fig. 7 shows the directly or indirectly addressed and achieved SDGs by implementing the CE strategies presented. The ecological added value of almost all CE strategies is clearly recognisable, which is expressed primarily in the benefits of resource conservation, environmental protection and health. The majority focus on recycling is again reflected in the fact that goal 9 regarding retrofitting of the industry can only rarely be achieved due to a lack of corresponding concepts. Compared with recycling, CE strategies such as reduce, reuse and remanufacture are considered to have a higher value in terms of sustainability, since they reduce the use of natural resources (SDG 12) and the cost of new production and logistics through the secondary benefits already described, and thus also reduce environmental pollution and CO_2 emissions (SDG 3 and 13). Reduced use of problematic materials and new fields of industrial activity are also conducive to the creation of secure and fulfilling jobs (SDG 8).

4.2.5. Challenges or obstacles for the implementation of a CE

Short-term economic benefits are the key intrinsic driver for industry. As explained, recycling strategies offer precisely these benefits to manufacturers. In the reviewed articles named barriers to the implementation of circular strategies beyond recycling are (from the industry's point of view), in descending order, difficult technical implementation, quality problems, insufficient database, organisational implementation, costs and lack of customer contact (Table 5). The table also shows the indicated reasons listed in the analysed literature that prevent closed-loop processes due to the lack of attention paid to them by industry.

The existence of a functioning CE is still first and foremost dependent on the political framework conditions. Only through appropriate administrative measures the industry will be forced to implement circular strategies beyond those that are purely economically motivated in

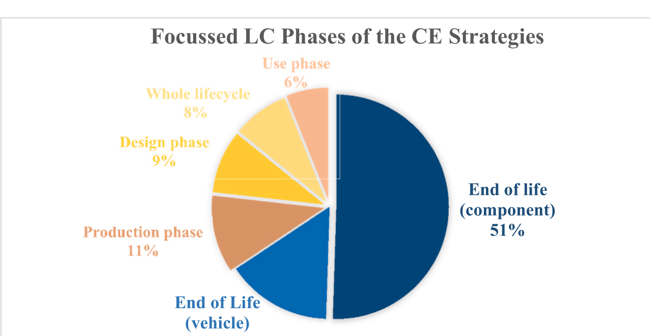

Fig. 6. Life cycle phases where CE strategies are applied or researched.

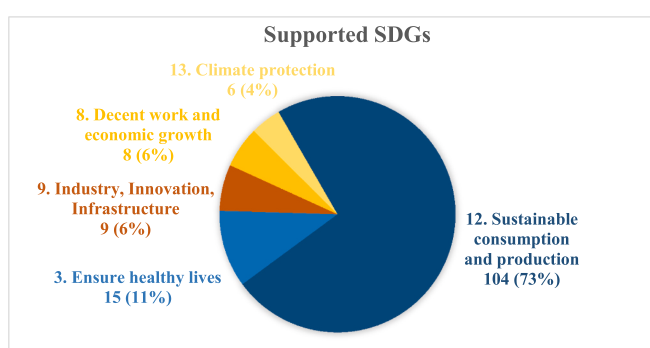

Fig. 7. SDGs achievable by the presented CE-strategies.

Table 5
Challenges for implementing CE.

Stakeholder/Perspective	Industry	Customer	Current PEP	Government
Challenges/Obstacles (n = no. of appearance)	Technical (26) Quality assurance (23) Database (15) Operational (13) Implementing costs (7) No end user contact (1)	Quality (8) Social acceptance (8)	No functional recycling of a certain material (3) Production costs (2) No holistic view (2) Dismantling costs (1) No common definition (1)	Poor legislation (9)

the short term. Also dependent on the political agenda are social factors such as environmental awareness among the population, occupational health and safety or wage costs. These factors in turn have a direct influence on purchasing and customer behaviour, which in turn leads to product requirements for manufacturers and thus to an indirect influence on corporate strategies by political goals via changed economic advantages, e.g. image and thus sales gains through environmental friendliness.

Various contributions point out that a lack of or weak political guidelines oppose an implementing of CE, whereby this does not only apply to poorer countries, where even disposal treatment is not regulated respectively monitored, a given example is Botswana (Mmereki et al., 2019), but deeper concepts are also prevented in industrialised countries by a lack of political coercion or incentive, e.g. in Germany (Reiter et al., 2020).

Approaches to functional reuse suggest how the technical and process-related difficulties listed in Table 5 and the associated qualitative difficulties can be solved. What is needed for implementation is a heightened awareness of the long-term economic benefits, also in industry, which could be achieved with the help of political guidelines and a change in consumer behaviour. Contributions that deal with a long-term rethinking in industry and society (refuse, rethink, reuse) or even pursue a completely new design approach (according to the logical procedure "Redesign") are strongly underrepresented or non-existent in the available works (cf. subsection 4.1). In addition to the described short-term economic obstacles, this is also partly due to the chosen research focus. Approaches that make the car and thus the chassis obsolete (refuse), e.g. by strengthening other modes of transport, were excluded in advance, as were possible product sharing approaches that only consider the car as a unit and do not deal with the chassis.

Further barriers result indirectly from the majority application of CE at the end of the product life cycle. Consideration of the handling of EoL components is missing in the product development process and in many LCAs, also due to the fact that ELV are usually handled by an independent recycling industry and/or end up in other markets (cf. e.g. annual report on vehicle disposal in Germany (Kohlmeyer, 2022)). Thus, ELV and components are outside the influence of manufacturers and related circular strategies are not in their sphere of interest.

4.2.6. Additional thoughts

4.2.6.1. Drivers of CE in the automotive sector. To identify the current CE drivers in the automotive sector, the texts were analysed according to the background (academic, industrial, administrative) of the authors. The graphical evaluation (Fig. 8) shows a clear majority for the academic background (50%). A combined academic and political background follows at a clear distance in second (24%) and collaborations between academic and industrial research in third place (11%), while a purely industrial author background is very rare. An exclusively political background could only be identified for one contribution (Commission, 2013).

In the second part of the analysis, the forcing influences presented in the texts were elaborated. As Fig. 9 shows, ecological and economic backgrounds are the most frequent motivations for dealing with the topic of CE.

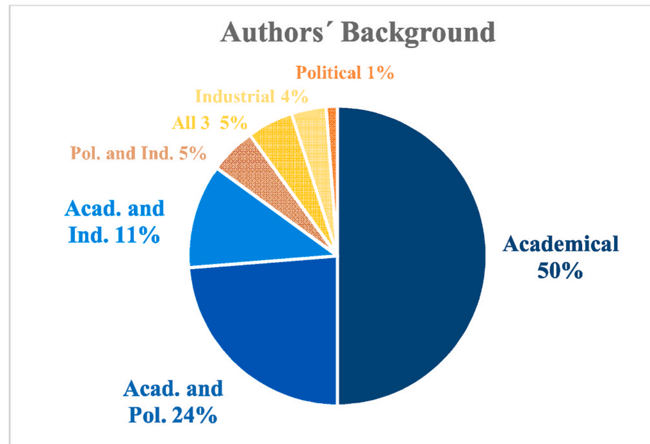

Fig. 8. Authors' background of the reviewed works.

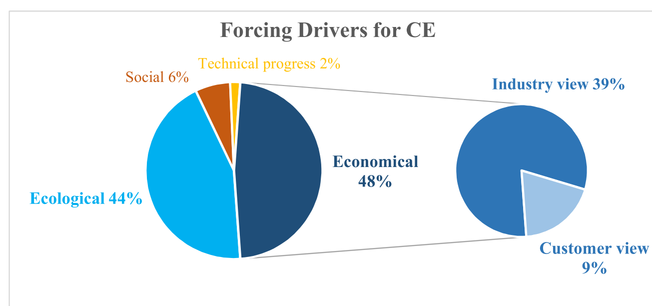

Fig. 9. Drivers of CE

4.2.6.2. Where is CE applied?. The respective political framework conditions are decisive in determining how the CE principles are applied. Strong administrative regulation promotes CE strategies that are designed with ecological and long-term economic and social benefits in mind, e.g. rethink, reuse, remanufacturing, equivalent recycling. The EU has played a pioneering role here with fixed quotas and producer responsibility. Comparable systems have been adopted by other countries, especially from Asia such as Japan and Korea. This can be explained on the one hand by the increased ecological awareness in politics and society, but on the other hand also by the scarcity of raw materials in these regions. The comprehensive paper (Commission, 2013) on remanufacturing looks specifically at the corresponding industrial structures in the USA and also shows a pronounced reuse practice for this market, justified mainly by the economic benefits. As distribution of the authors' regional affiliations shows (Fig. 10), a certain environmental awareness has also developed in many emerging countries such as China, India, Malaysia etc. in recent years. However, administrative requirements for industry are still much less pronounced here, and so are the infrastructural framework conditions for the implementation of CE. A large part of the efforts here focusses on waste management, from which recycling is increasingly dealt with, tending towards downcycling. In

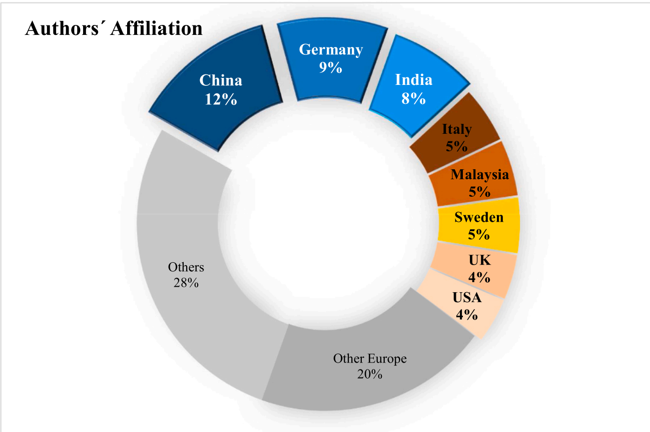

Fig. 10. Regional affiliation of all named authors.

poorer countries, there are only a few examples of CE, which mainly relate to the problem of waste and the associated ecological and health risks, and mainly deal with the issue of downcycling to prevent landfilling, which has been common up to now.

It can be summarised that wherever CE is on the political agenda for various reasons, research activities are naturally also pushed. The significantly higher share of academic research in the publications identified can certainly also be justified by the fact that OEMs and large suppliers may only be dealing with this topic internally as a matter of priority. As already explained, remanufacturing is common practice for after-sales service. However, this can only be seen in a few places in the available sources. Based on additional research, however, it can be assumed that all (larger) OEMs and suppliers are active in this field, e.g. (Ellenmacarthurfoundation, 2020), (Mercedes Benz, 2023).

What can be clearly seen from the data is the low level of support for academic research in the field of the circular economy by the automotive industry. Science, in turn, is closely linked to regional political goals. If these goals are absent or only weakly developed, as is the case in many countries in Africa and South America, research activities are also correspondingly low. In the poorest regions, an additional factor is that industrial structures that enable or require a circular economy may not even exist. China has the largest share of the publications found (12%), followed by Germany (9%) and India (8%) (c.f. Fig. 10). Other Europe/ Others includes all countries that have a share of 3% or less.

4.2.6.3. Which chassis components are focused by which CE concepts?. As shown in subsection 4.1, in the chassis assembly, the focus of CE is primarily on tyres, followed by brake components, especially brake pads. In the numerous contributions on the handling of used tyres, reference is made to the enormous number of EoL tyres and the associated problems (cf. Fig. 11, multiple answers possible).

However, the same applies analogously to many other components of the chassis that are installed several times in vehicles (brakes, dampers, steering knuckles, etc.). The concentration on the tyre component or the need for research is rather due to its composition. While mainly metal-based components of the chassis such as steering knuckles, brake discs, etc. can be recycled quite easily due to their material homogeneity, a tyre consists of an inhomogeneous material mix of metals and non-metals, some of which are considered environmentally hazardous, at least in the case of thermal energy recovering, e.g. sulphur compounds, which makes handling at the EoL more difficult. The same also applies to currently used brake pads. The main drivers for the focus on these two components are therefore ecological goals. As both are highly safety-critical applications, a functional reuse beyond material recycling makes high demands on quality and is the content of only a few contributions (Fig. 12).

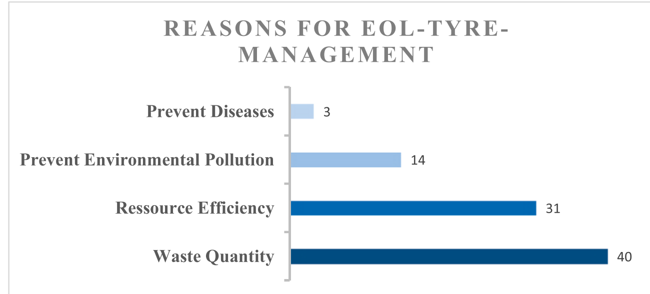

Fig. 11. Reasons for the implementation of an EoL-Tyre-Management.

5. Discussion

The main outcomes of the conducted literature research can be comprised and reflected as follows.

Understanding of the term of circularity in the automotive sector: The review shows that in the automotive sector a product is already said to be circularly if a certain material proportion can be used in a new product. This understanding is mainly focused on a level of materials, i. e. material recycling not on the functional reuse and further use of product components and a related product design.

Implemented strategies of the CE in the automobile industry: In this study, an adapted R-framework considers a relatively wide range of CE strategies throughout the product life cycle. Corresponding to the understanding of the term of circularity in the automotive industry, recycling in the form of recovering materials from ELV and components for further use of these materials in a similar or unrelated purpose is often used. Contributions that deal with a long-term rethinking in industry and society (refuse, rethink, reuse) or even pursue a new design approach (redesign) are strongly underrepresented in the available works. A functional reuse in new vehicles that is already pursued in series production is not documented by the database. The development of durable components that can be used over several vehicle LC is not the goal of today's automotive engineering process and the corporate strategies. For the aftermarket, however, remanufactured spare parts are offered. Furthermore, the refuse strategy does not play a role in the reviewed literature, although it was named as an important lever for waste avoidance and resource conservation. For the mobility sector, the reduction of individual mobility and local production along with the strengthening of other modes of transport would be essential (refuse) measures to force sustainability. However, current trends in globalisation, consumption and urbanisation clearly point in a different direction and the (automotive) industry is understandably not interested in avoiding its products.

Focused phases of the automobile LC: The majority of the analysed sources which discuss strategies of circular economy refers to the EoL of components or vehicles. Examples of addressing the incorporation of CE

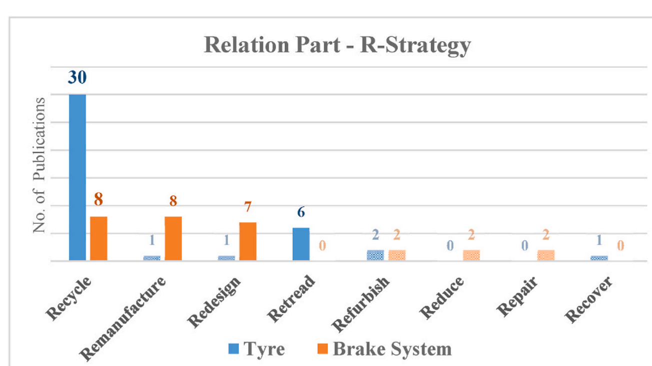

Fig. 12. Treated chassis parts and related R-strategies.

strategies in other phases, especially the product development process, are rare.

Achievable sustainable development goals: In the analysed literature, the implementation of CE strategies is supposed to reduce the use of natural resources (SDG 12). In this context, reduce, reuse and remanufacture are considered to have a higher potential in terms of sustainability than recycling. SDG 3, 9, 8 and 13 are further goals which are considerable influenced by CE strategies.

Challenges for the implementation of a CE: The literature was analysed considering the perspectives of industry, customers and government. Obstacles to the implementation of CE strategies from an industry perspective are quality problems, difficult technical implementation, insufficient database, costs and lack of customer contact. Overall the main identified challenges are quality problems, a changed product engineering process and inadequate regulations. Legislation strongly influence the implementation of the CE strategies. Recycling and recovering quotas for ELV in connection with an extended producer responsibility have been introduced in many countries in the past, e.g. in Japan, Korea and the EU (Despeisse et al., 2015), (Zhang and Chen, 2014). For instance, the “End-of-Life Vehicles Directive” currently in force in Germany stipulates a recycling rate of 85% (of weight) and a total recovery rate of 95% (Bundesamt der Justiz). However, these demands, which seem high at first glance, hide the fact that the share of reused components in the sense of the definition of a sustainable circular economy drawn up according to the authors’ understanding in section 2 is significantly lower. The reuse rate of metals and non-metals for ELV in Germany, for example, was 3.6% in 2020 and thus even lower than in 2014 (4%) (Kohlmeyer, 2022). All remaining components that are included in the total recycling rate are therefore only recycled, i.e. separated at great expense and re-melted or shredded and used as fillers (downcycled) or even only used for energy generation, i.e. incinerated. This could be confirmed by the results of this work. This situation is in stark contrast to the objective of a high circularity, e.g. comparable to the new Circular Economy Action Plan (European Commission). This problem may even increase with alternative materials for lightweight construction purposes or to avoid problematic raw materials (Götze et al., 2018).

The circular activities in both industry and research are reduced if the legal obligation decreases. In various industrialised countries there are weaker regulations, e.g. Malaysia (Jamaluddin et al., 2022), or even no specific ELV legislation, e.g. it is the case in USA, Canada or India (Saidani et al., 2019), (Arora et al., 2019). Here, the ELV industry is mainly market driven, which may result in an even greater use of procedures with short-term economic added value. Further reduced regulation and lack of infrastructure favour the disposal of end-of-life vehicles by an informal industry. In very poor countries, this effect still may be exacerbated and favour the use of environmentally damaging energy recovery or landfilling as the preferred means of ELV disposal (Mmereki et al., 2019), (Nkosi et al., 2019), (Zarei et al., 2018).

Drivers of the CE in the automotive industry: Accordingly, there is a higher number of publications from authors - most of them with an academic background, mainly addressing economic and ecological motivations - affiliated in countries with a higher degree of regulations. Differences in regulations can cause far-reaching problems. For example, due to the lack of legal regulations, the problem of ELV disposal is partly shifted to other regions where landfilling is often still the method of choice. Additionally, valuable resources are lost. A weak regulation and even with the above-mentioned quotas show that even in industrialised countries, current legislation is not sufficient to transfer more far-reaching circular economy structures into industrial production. The advantages at various levels of sustainability have been clearly demonstrated and should be the main drivers here. The increasing scarcity of natural resources is also expected to be a significant economic driver in the future. Downcycling should be increasingly replaced by equivalent recycling and functional reuse to preserve expensive raw materials. A society or industry that adapts to this at an early stage can secure decisive advantages. However, this requires a changed global approach that takes all influencing factors into account. Though, it becomes difficult for individual countries to implement legal obligations nationally without risking the economically motivated migration of companies.

Beside governmental regulations, a changed product design process was identified as essential for the implementation of CE principles. New methods presented in the contributions as Design for CE, Ecodesign, extended LCA or similar (cf. Table 4) can best be summarised under redesign in analogy to the R-strategies used. Their implementation should consequently become an essential goal of legislation. The results of this review were able to highlight the links between legislation, social acceptance and research and industry activities regarding a circular economy. At the same time, the discrepancy between the claim, e.g. in the form of the EU action plan at the political level or with promotionally effective concept vehicles by the industry, and the reality with recycling (downcycling) as the primarily used strategy (compare i.e. (AUDI AG, 2023), (Seidel, 2022)) in the industry was shown.

As an answer to the main research question it can be stated, that reuse and circularity are insufficiently or not at all considered in the current automotive PEP. This raises the question of how this can be strengthened apart from the direct economic benefits. The existing practice reusing restored parts in the after sales market demonstrate, that product quality can be ensured with economical effort. The continued use in new vehicles therefore also requires a changed mindset by the customers, which can be achieved through increased awareness and corresponding incentives from politics. On behalf of the industry, monitoring during operation (e.g. during the first LC) to ensure safety and quality can create corresponding trust and would be a further product feature that would already have to be considered in the PEP. However, it is remarkable that digitalization and artificial intelligence are not very much highlighted in the respective papers with automotive background as digitalization and CE are vividly discussed in the overall CE literature, e.g. in (Arnold et al., 2019), (Al-Swidi et al., 2023). Here, further research is needed.

5.1. Limitations

The authors acknowledge that this work is limited by several factors. Initially, the analysis is based on the presented keywords and might exclude some relevant articles using different wordings. In the future, statistical analysis could be conducted using meta-analysis to provide more robust and meaningful results. The decision to define reusing out of the vehicle as an exclusion criterion, as explained in 4.2.1, may lead to other CE strategies not being considered. In particular, this may be the reason for the lack of concepts for avoidance or repurposing if the terms “refuse” or “repurpose” were not explicitly included. This shows that the literature search with the defined R-framework could exclude other CE practices, e.g. such as sustainable supply chain management. Future studies may consider this as a research direction. Moreover, in line with the EU’s pioneering role, definitions and argumentations, especially in the first two chapters of this work, often represent a European perspective. So, there is a potential European bias in our paper. Nevertheless, the literature review includes publications worldwide and as a result it can be stated, that Chinese and European researchers publish most in the field of automotive CE. This statement is based exclusively on the final reviewed literature. Both our search string and our exclusion criteria did not discriminate against literature from other countries, but the data selection is limited to English-language articles. This exclusion criterion may therefore lead to language bias. We recognise that there are valuable contributions and best practices from other regions, e.g. Japan, that have led to significant advances in ELV handling, CE legislation and recycling practices.

The methodological approach of this study must also be viewed critically about the restrictive focus on the chassis. However, the analyses of further literature beyond Appendix A1 and the important role of the chassis lead to the conclusion that the insights gained in this work also apply to the other (less important) assemblies and regardless of the vehicle class. Another indication of this are the results of the introduced review (Valladares Montemayor and Chanda, 2023) from the OEM perspective. Despite the different approach - the OEM perspective is rather underrepresented in the present study due to the research method, where mainly scientific papers have been found, while the academic perspective is neglected in the other-the key findings, the focus on recycling and the underrepresentation of circular economy at a high level, are consistent in both studies. However, neither can answer the extent to which individual OEMs and suppliers are working in the background to implement high-quality CE strategies.

6. Conclusions

The application of circular economy principles offers probate means for increasing sustainability in production and consumption. Sustainability has become a major focus of public discussion in recent years. Due to this social pressure, the requirements of legislation and not least due to the expected competitive advantages, the (automotive) industry has incorporated a circular economy into their corporate strategy in many places. However, this review shows the activities to date equate the circularity of a product with recycling. Beyond that, if any, only isolated solutions for specific, component-related issues, e.g. the handling of used tyres in the focused area of chassis are offered. This applies both to the industry and to most (academic) research activities. To a large extent, the automotive industry still follows a linear economic model. Existing practices for reusing reprocessed components are limited to spare parts business. The handling of partial components at the end of the vehicle's life has not yet been sufficiently considered in the product engineering process. Any circular product design concepts have so far been insufficiently developed or even implemented in the automotive industry.

Based on the knowledge gained, the review authors therefore see three priorities: (i) Corresponding circular concepts must start already in the product development phase and (ii) take into account the entire life cycle extended with the end of life handling. Ultimately, this means nothing less than the need for a completely changed PEP (product design for circularity) to transfer the topic circular economy from buzzword to practice. By using digitalization and a more networked product creation corresponding methods must be practicably applicable to find their way into industry with the help of demonstrating the advantages for society, economy and consumers. (iii) Concepts are sought that enable the goals of a CE to be achieved as universally as possible, i.e. at least for the respective industry sector independently of components. This is where the crucial R&D demand is seen.

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Declaration of competing interest

No conflict of interest.

Data availability

Data will be made available on request.

Appendix A1. Reviewed literature

No. in Table 4	First author	Title	Year of publication	DOI (if available)
(1)	Agunsoye	Recycled ceramic tile composite for automobile applications, a comparative study with Nissan Jeep Cherokee brake pad.	2018	10.14456/EASR.2018.30
(2)	Aziz	Establishment of Engineering Metrics for Upgradable Design of Brake Caliper.	2017	10.1007/978-3-319-57078-5
(3)	Aziz	Evaluating design for upgradability at the conceptual design stage.	2016	10.11113/jt.v78.9145
(4)	Banar	Characterization of pyrolytic oil obtained from pyrolysis of TDF (Tire Derived Fuel).	2012	10.1016/j.enconman.2012.03.019
(5)	Barnabas	Recycling of waste crumb rubber into a commercial materials.	2022	10.1007/s42464-021-00103-w
(6)	Baskar	Experimental studies on mechanical and morphological property of the natural and SBR/BR hybrid rubber.	2021	10.1016/j.matpr.2020.07.111
(7)	Bowles	Sustainable rubber recycling from waste tyres by waterjet: A novel mechanistic and practical analysis.	2020	10.1016/j.susmat.2020.e00173
(8)	Bunget	Impact-acoustic evaluation method for rubber–steel composites: Part I. Relevant diagnostic concepts.	2015	10.1016/j.apacoust.2014.10.014
(9)	Cecchel	A comparative cradle-to gate impact assessment: Primary and secondary aluminum automotive components case.	2018	
(10)	Cecchel	Lightweight of a cross beam for commercial vehicles: Development, testing and validation.	2018	10.1016/j.matdes.2018.04.021
(11)	Cheraghali-pour	An integrated approach for collection center selection in reverse logistic.	2017	10.5829/ije.2017.30.07a.10
(12)	Daaboul	Reverse logistics network design: a holistic life cycle approach.	2014	10.1186/s13243-014-0007-y
(13)	Dabić-Ostojić	Applying a mathematical approach to improve the tire retreading process," Resources, conservation, and recycling.	2014	10.1016/j.resconrec.2014.02.007

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(continued)

No. in Table 4	First author	Title	Year of publication	DOI (if available)
(14)	Dayang	Effect of ground Tyre rubber devulcanisates on the properties of a passenger car Tyre tread formulation.	2014	10.4028/www.scientific.net/amr.844.425
(15)	Dell'Era.	Carbon powder material obtained from an innovative high pressure water jet recycling process of tires used as anode in alkali ion (Li, Na) batteries.	2018	10.1016/j.ssi.2018.06.008
(16)	Denkena	Measures for energy-efficient process chains.	2021	10.1016/j.procir.2021.01.105
(17)	Di Bella	Exploitation and energy recovery of fluff: smart solutions in a prospective of circular economy.	2019	
(18)	Diener	Scrapping steel components for recycling—Isn't that good enough? Seeking improvements in automotive component end-of-life.	2016	10.1016/j.resconrec.2016.03.001
(19)	dos Santos	Tire waste management: an overview from chemical compounding to the pyrolysis-derived fuels.	2020	10.1007/s10163-020-00986-8
(20)	Dwivedi	Utilization of waste spent alumina catalyst and agro-waste rice husk ash as reinforcement materials with scrap aluminium alloy wheel matrix.	2020	10.1177/0954408920930634
(21)	Elhilali	Towards the development of an optimized numerical model of the brake system pad with natural material.	2021	10.1016/j.matpr.2021.02.113
(22)	Formela	Characterization and properties of LDPE/(ground tire rubber)/crosslinked butyl rubber blends.	2014	10.1002/vnl.21363
(23)	Furberg	Dissipation of tungsten and environmental release of nanoparticles from tire studs: A Swedish case study.	2019	10.1016/j.jclepro.2018.10.004
(24)	Gnanaraj	Sustainable waste tire derived carbon material as a potential anode for lithium-ion batteries.	2018	10.3390/su10082840
(25)	Gnitko	Designing an improved structure of the tool for repairing the brake pipe connectors in vehicles.	2021	10.15587/1729–4061.2021.224912
(26)	Gonçalves	Discrete event simulation as a decision-making tool for end-of-life tire reverse logistics in a Brazilian city consortium.	2019	10.1007/s11356-019-05559-3
(27)	Gradin	Comparative life cycle assessment of car disc brake systems—case study results and method discussion about comparative LCAs.	2020	10.1007/s11367-019-01704-9
(28)	Guo	A new strategy for high-value reutilization of recycled carbon fiber: Preparation and friction performance of recycled carbon fiber felt-based C/C–SiC brake pads.	2019	10.1016/j.ceramint.2019.05.191
(29)	Hoyer	Neuartige Warmmahltechnologie zum Recycling von Elastomeren und Analyse prozessbedingter Eigenschaften.	2018	
(30)	Jacob	Dealing with emerging waste streams: Used tyre assessment in Thailand using material flow analysis.	2014	10.1177/0734242x14543554
(31)	Kannan	Analyzing the drivers of end-of-life tire management using interpretive structural modeling (ISM).	2014	10.1007/s00170-014-5754-2
(32)	Karakoyun	Holistic life cycle approach for lightweight automotive components.	2014	10.1051/metal/2014034
(33)	Krini	Investigation of a reliability prevention model for remanufactured systems in automotive.	2015	10.1109/ICAT.2015.7340541
(34)	Krotil	Refabrikation in der Nutzfahrzeug-Industrie.	2019	10.1007/s35144-019-0423-8.
(35)	Li, L.	Mechanical properties of recycled butyl rubber/virgin butyl rubber composite.	2013	10.4028/www.scientific.net/amr.621.8
(36)	Li, Y.B.	Hot forging die composite manufacturing technology.	2013	10.4028/www.scientific.net/amr.712-715.615
(37)	Lind	Exploring inter-organizational relationships in automotive component remanufacturing.	2014	10.1186/2210-4690-4-5
(38)	Lonca	Does material circularity rhyme with environmental efficiency? Case studies on used tires.	2018	10.1016/j.jclepro.2018.02.108
(39)	Lyu	Recycling of worn out brake pads − impact on tribology and environment.	2020	10.1038/s41598-020-65265-w
(40)	Mmereki	Status of waste tires and management practice in Botswana.	2019	10.1080/10962247.2017.1279696
(41)	Mohaved	A novel industrial technique for recycling ethylene-propylene-diene waste rubber.	2015	10.1016/j.polymdegradstab.2014.11.003
(42)	Mok	Determination of failure cause in remanufacturing.	2015	10.1016/j.proeng.2015.01.337

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No. in Table 4	First author	Title	Year of publication	DOI (if available)
(43)	Noryani	Material selection of natural fibre using a stepwise regression model with error analysis.	2019	10.1016/j.jmrt.2019.02.019
(44)	Nugroho	Android and cloud-based application development to predict remaining age of four-wheeled vehicle brake pad with varied driving behaviour.	2021	10.1088/1757-899x/1116/1/012108
(45)	de Zabalegui	Development of a new methodology to use recycled Secondary Aluminum substituting primary A356 aluminum alloy in safety components in low pressure technology.	2014	
(46)	Okoro	Modification of waste tire pyrolytic oil as base fluid for synthetic lube oil blending and production: waste tire utilization approach.	2020	10.1007/s10163-020-01018-1
(47)	Ounsaneha	Assessment of human health impact based on life cycle assessment: A case study of Thai retread tire.	2020	10.1088/1757-899x/773/1/012038
(48)	Öz	Braking performance and noise in excessive worn brake discs coated with HVOF thermal spray process.	2017	10.1007/s12206-017-0106-4
(49)	Pai	Tribological response of waste tire rubber as micro-fillers in automotive brake lining materials.	2020	10.1007/s40544-019-0355-6
(50)	Papakostas	Computer-aided design assessment of products for end of life separation and material handling.	2015	10.1016/j.cirp.2015.04.023
(51)	Pedram	Integrated forward and reverse supply chain: A tire case study.	2017	10.1016/j.wasman.2016.06.029
(52)	Pereira	Forecasting scrap tires returns in closed-loop supply chains in Brazil.	2018	10.1016/j.jclepro.2018.04.026
(53)	Petrov	Improving the efficiency of recycling used tires.	2021	10.1007/978-981-33-6208-6_29
(54)	Qiang, W.	Process and reinforcement mechanism about dislocation remanufacturing retreaded OTR tires by using waste steel.	2018	10.1088/1755-1315/189/6/062014
(55)	Qiang, W.	Loading deformation characteristic simulation study of engineering vehicle refurbished tire.	2018	10.1088/1755-1315/153/4/042037
(56)	Rajak	Multi-objective mixed-integer linear optimization model for sustainable closed-loop supply chain network: a case study on remanufacturing steering column.	2022	10.1007/s10668-021-01713-5
(57)	Ran	Effect on the model of government-subsidized dual-channel closed-loop supply chain: Taking automobile tire recycling as an example.	2021	10.1088/1755-1315/820/1/012013
(58)	Reiter	Protect our health with cleaner cars – how to gain customer acceptance for air pollution decreasing retrofit purchase.	2020	10.1007/978-3-030-50341-3_13
(59)	–	Remanufactured Goods: An Overview of the U.S. and Global Industries, Markets, and Trade.	2012	
(60)	Riemer	Wiederverwertung von Altreifen in Metall-Kunststoff-Verbunden.	2017	10.1007/s35725-016-0098-5
(61)	Saiwari	Devulcanization of Whole Passenger Car Tire Material.	2013	
(62)	Satué	Functional vehicle design for urban mobility.	2013	10.4271/2013-01-0033
(63)	Schmidt	Energieeffizientes Altgummi-Recycling ohne Chemikalieneinsatz.	2015	
(64)	Singh	Application of waste tire rubber particles in non-asbestos organic brake friction composite materials.	2018	10.1088/2053-1591/aaf684
(65)	Sun	Research on the virtual assembly-disassembly and repair of the automobile drive axle.	2013	10.4028/www.scientific.net/amr.605-607.646
(66)	Szotkowski	Jig Design for Disassembly of Undercarriage Component.	2018	
(67)	Thai	Recycling of waste tire fibers into advanced aerogels for thermal insulation and sound absorption applications.	2020	10.1016/j.jece.2020.104279
(68)	Thuliez	Softcar: un nouveau concept de véhicule électrique.	2015	10.5169/seals-856630
(69)	Torretta	Treatment and disposal of tyres: Two EU approaches. A review.	2015	10.1016/j.wasman.2015.04.018
(70)	Tsai	Status of waste tires' recycling for material and energy resources in Taiwan.	2017	10.1007/s10163-016-0500-5
(71)	Tsang	Uses of scrap rubber tires.	2013	

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No. in Table 4	First author	Title	Year of publication	DOI (if available)
(72)	Van Hoek	Best practice for de-vulcanization of waste passenger car tire rubber granulate using 2-2′-dibenzamidodiphenyldisulfide as de-vulcanization agent in a twin-screw extruder.	2021	10.3390/polym13071139
(73)	Vermeulen	Sequential bioleaching of copper from brake pads residues using encapsulated bacteria.	2017	10.1016/j.mineng.2016.11.010
(74)	Vimal	Integrating sustainability and remanufacturing strategies by remanufacturing quality function deployment (RQFD).	2021	10.1007/s10668-020-01211-0
(75)	Wang, X.	Healable, recyclable, and mechanically tough polyurethane elastomers with exceptional damage tolerance.	2020	10.1002/adma.202005759
(76)	Wang, Y.H.	Production of thermoplastic elastomers based on recycled PE and ground tire rubber: Morphology, mechanical properties and effect of compatibilizer addition.	2018	10.3139/217.3544
(77)	Wilde	Ressourceneffizienz – aktuelle Herausforderungen und Strategien der Robert Bosch GmbH.	2014	10.1007/s00550-014-0325-4
(78)	Wurster	Creating a circular economy in the automotive industry: The contribution of combining crowdsourcing and Delphi research.	2021	10.3390/su13126762
(79)	Xu	Replacing commercial carbon black by pyrolytic residue from waste tire for tire processing: Technically feasible and economically reasonable.	2021	10.1016/j.scitotenv.2021.148597
(80)	Zheng	Dissolving used rubber tires.	2020	10.1039/c9gc03545a
(81)	Zhong	Pyrolytic preparation and modification of carbon black recovered from waste tyres.	2020	10.1177/0734242X19869987
(82)	Zhou	A quality evaluation model of reuse parts and its management system development for end-of-life wheel loaders.	2012	10.1016/j.jclepro.2012.05.037

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