Assessing rebound effects in circular economy: insights from the automotive industry

Mariantonietta Ferrante [1*], Micaela Vitti [1], Giorgio Mossa [1], Claudio Sassanelli [1]

* *Department of Mechanics, Mathematics, and Management, Polytechnic University of Bari, Via Orabona, 4 70125 – Bari – Italy (m.ferrante6@phd.poliba.it, micaela.vitti@poliba.it, giorgio.mossa@poliba.it, claudio.sassanelli@poliba.it)*

Abstract: Circular Economy (CE) practices are adopted in the manufacturing industry to minimise the use of virgin and hazardous materials and the production of waste, turning out to be effective in addressing multiple sustainable development goals. Circular manufacturing (CM) involves several strategies, such as remanufacturing, product-service systems, waste management, and disassembly. Despite all the sustainable benefits associated with the implementation of CM strategies, they could also be hampered by the occurrence of negative consequences, the so-called rebound effect (RE). RE is defined as an efficiency improvement in production that unexpectedly increases demand for and consumption of resources. In trying to understand how, where, and why RE occurs in applying CE in manufacturing, the literature revealed a main gap: the lack of industrial applications. To address this main gap, the automotive industry, which is one of the main contributors to pollution, has been investigated. A systematic literature review to explore RE within the automotive industry has been conducted, and a series of practitioners belonging to automotive companies have been interviewed to evaluate their CE adoption and RE awareness. The objective was to investigate the level of awareness and knowledge of the possible occurrence of different types of RE within CE in the automotive industry, relying on both theoretical and practical investigations. In particular, the research evaluated and raised companies' awareness about REs' possible occurrence, detected the principal strategies adopted by companies to maximise resource value and minimise negative environmental impacts, and explored current practices in manufacturing on how to detect, reduce, and prevent possible negative consequences that could decrease the expected benefits of CE. Finally, this research provides insights to both managers and policymakers, also defining a baseline for future research on how to cope with the RE of CE.

Keywords: circular economy; rebound effect; systematic literature review; interview; automotive

1. Introduction

Circular economy (CE) is a model of production and consumption to minimize waste and maximize the use of virgin materials (Geissdoerfer et al., 2017; Kirchherr et al., 2017). CE practices, such as reduce, reuse, and recycle, are being largely adopted in the manufacturing industry as circular manufacturing (CM) (Garza-Reyes et al., 2019), due to their capability to address multiple sustainable development goals (SDGs) (e.g., goals number 7, "affordable and clean energy", and number 12, "sustainable consumption and production") (Sachs, 2012). Indeed, several CM strategies (as disassembly, waste management, product-service systems, remanufacturing, and recovery (Acerbi et al., 2024)) have been defined and implemented along the time as a solution to achieve environmental, economic, and social benefits. Being fostered by digital technologies, in CM the role of data is key, assuming a strategic role in supporting practitioners' decision-making processes and leading to the definition of data-driven CM (Acerbi et al., 2022).

In this context, the automotive industry assumes a relevant role. In 2010, the transport sector was responsible for about 23% of global direct CO_2 emissions. In 2022, greenhouse gas emissions (GHG) from the transport sector continued to grow by 2.7% in Europe (European Environment Agency (EEA), 2023). In this specific industry, the importance of data is becoming always more essential, due to the need pushed by European Commission of introducing the digital product passport (European Health and Digital Executive Agency (HaDEA), 2023). Impelled by incoming regulations, automotive companies are implementing data-driven CM strategies, particularly with regard to remanufacturing capacity (Maldonado-Guzmán et al., 2021), boosted by the implementation of Industry 4.0 technologies (Rizvi et al., 2023). The circular strategies allow automotive companies to reduce carbon emissions and non-renewable resource consumption (Prochatzki et al., 2023).

Despite all the sustainable benefits achieved through the adoption of CM strategies, some negative effects could arise, among these the rebound effect (RE). RE is defined as an efficiency improvement that leads to an undesirable increase in consumption of resources, decreasing the expected initial benefits (Zink and Geyer, 2017). From a sustainable perspective, RE could reduce the environmental, economic, and social benefits obtained at multiple levels of analysis (i.e., micro, meso, and macro) involving both producers and consumers and their interactions with cities, regions, and countries (Font Vivanco et al., 2022). At each level of analysis, a different type of RE could occur (i.e., direct, indirect, economy-wide, and transformational) (Otto et al., 2014). Direct RE refers to an increase in demand and consumption of the same product due to an efficiency improvement leading to a related enhancement in price, production, or perception, involving at the micro level the producer and consumer (Otto et al., 2014). One example is the electric car. In fact, greater efficiency in the use of an alternative fuel leads to more driving (Walnum et al., 2014) Indirect RE occurs when an improvement in production in one product generates an increase in demand or supply of other products at meso level, involving consumer and producer within the market of interest (Sorrell, 2007). For instance, the electric scooter can substitute walking, cycling, or public transportation, even for short routes.

Economy-wide RE involves both direct and indirect effects, leading to increased efficiency and changes in supply and demand at the market level (Sorrell and Dimitropoulos, 2008). As proof, photovoltaic panels produce energy efficiently while increasing energy demand and use.

Transformational RE refers to wide-scale changes in the economy and society due to efficiency improvements at the macro level (Greening et al., 2000). An example could be second-hand clothes that offer an additional alternative to new clothes, increasing production and demand even more.

To this concern, it is important to understand how and where RE occurs within the application of CE practices in manufacturing to prevent and avoid these negative effects and maximise the circular benefits. In the domain of CE-RE, five dimensions (i.e., Business model, Drivers, Product lifecycle management (PLM), CM ecosystem, and Socio-economic aspects) have been detected in which the negative effects due to the implementation of CE practices could occur (Ferrante et al., 2023). In addition, different factors (i.e., characteristic of a specific dimension that could generate or be relevant in the occurrence of REs) have been identified for each dimension, such as *innovative and sustainable circular product* from PLM, *sustainable purchase intention* from Socio-economic aspects, and *organisational and financial drivers* from Drivers, which, related to each other, could generate different types of RE (Ferrante et al., 2024). Nevertheless, the knowledge of this possible negative effect by manufacturers and users is limited, as revealed by a previous study of the literature, where a lack of industrial applications has emerged. To address this gap, the aim of this research is to investigate the level of awareness and knowledge about the possible occurrence of different types of RE within CE in the automotive industry through theoretical and practical analysis, to bridge the gap between theoretical knowledge and the manufacturer's level of awareness about RE in the automotive industry. According to this purpose, a systematic literature review (SLR) to investigate the occurrence of RE, which has been evaluated in different areas (i.e., energy, economic, and environmental) where efficiency gains arose (Barkemeyer et al., 2022), within the automotive industry has been conducted. This theoretical study aimed to recognise and detect the different types of RE that could occur in the sector considered in the literature. Secondly, a series of practitioners employed in this kind of company have been interviewed to assess in practice how circular strategies are adopted and measured and unveil the possible negative consequences that could arise.

The paper is structured as follows. Section 2 presents the research methodology adopted to conduct the SLR and the interviews. Section 3 delineates the results obtained through the literature analysis and the conducted interviews. In Section 4 the main results obtained are discussed and contributions and implications reached are provided. Section 5 concludes the paper with a focus on research limitations and future developments.

2. Research methodology

To investigate the level of awareness and knowledge of the possible occurrence of different types of RE within CE in the automotive industry, a SLR has been conducted, following the five steps (Denyer and Tranfield, 2009) represented in Fig. 1.

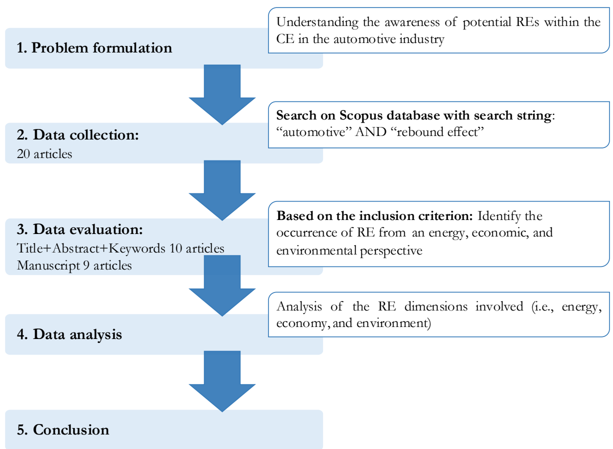

Figure 1: Overview of the research methodology adapted from Biolchini et al. (2005)

The first step is the Problem formulation, represented by the need to understand the awareness of the possible REs within CE strategies with a focus on in the automotive industry. The second step is the Data collection, which was performed on the Scopus database through the following search string: *"automotive" AND "rebound effect"*. The search was carried out without restrictions in terms of type of scientific publications and period, with a filter on the English language, providing a set of 20 documents. In the third step, data evaluation, relevant articles were selected according to an inclusion criterion, or if they present a type of CE-RE evaluated from an energy, economic, and environmental perspective. These three perspectives represent the areas where the efficiency gains occurred according to the literature (Barkemeyer et al., 2022). After this selection, a total of nine papers were selected for the final analysis. Within the following Data analysis step, the selected papers were analysed according to the RE dimensions used in the inclusion criterion, and also characterised by the factor of CE-RE domain involved. Finally, in the last step, the key findings of the analysis were presented.

In addition, to address the practical objective of this research, which is to investigate whether companies that have already adopted circular strategies in their processes

and organisations are aware of the possible occurrence of negative consequences, an interview protocol was developed and a set of semi-structured interviews was conducted.
Three companies were selected for the interview. These companies within the automotive industry were involved in the production of different parts of the car, including tyres, the design of the whole car, and specific components. These different perspectives offered a global insight into the adoption of CE practices in the automotive industry. In doing that, based on a protocol, three separate semi-structured interviews have been conducted online, involving at least one person from the company involved. The interview protocol is based on six questions addressing the CE transition in the company, which are reported below:

1. Interviewees profile and information: question aiming to understand the role of the interviewees in the company and his involvement in pursuing a circular transition.
2. Company information about CE: question aiming to understand the company's already put-in-place actions and activities for achieving a circular transition.
3. Circular strategies adopted: question aiming to explore the circular strategies already implemented in the company.
4. Benefits achieved: question aiming to identify the benefits obtained after the adoption of circular strategies.
5. Methods to capture circular benefits: question aiming to understand whether and how the benefits obtained from the implementation of circular strategies are measured.
6. Negative effects detected: question aiming to explore the negative consequences (or at least the related companies' awareness) due to the implementation of circular strategies.

In Table 1, information about the single interviews is reported.

Table 1: Interviews details

Automotive company	Employee role	Interview duration	Interview date
A	Mechanical Department Manager	25 min	2024/02/19
B	Environmental Innovation Manager	25 min	2024/02/20
C	Power Department	20 min	2024/03/04

3. Results

The nine papers selected through the SLR are quite recent, covering a time period from 2018 to 2021. The analysis of the first author nationalities showed a higher contribution from Europe (5 papers), while the remaining four were two from the United States, one from Australia, and one from Japan. Most of the selected papers (eight) were published in journals, and only one was in international conference proceedings. The journals contributing most to the research were *Journal of Cleaner Production* and *Energy Policy* with two papers, and then *Ecological Economics*, *Capitalism, Nature*, *Socialism, Technological Forecasting and Social Change*, and *Energy Economics* with one paper each. In terms of the type of research conducted, most of the selected papers provided an analytical method of analysis (four papers), and three papers presented theoretical research followed by an application case. The last two papers provided a theoretical study and a survey about the use of hybrid-electric vehicles.

This SLR aimed to recognise and detect the different types of RE that could occur in the automotive industry, as presented in the literature. In fact, the nine selected papers were analysed to identify the RE dimension involved in the sustainable practices adopted by companies and also to clarify the research domain and gaps, as reported in Table 2.
In the automotive industry, RE occurs in different dimensions (i.e., energy, economic, and environmental) as presented by (Barkemeyer et al., 2022) and may involve one or two dimensions simultaneously.
In the energy-economic dimensions, improvements in fuel use (savings) reduce CO_2 emissions and decrease prices (Greene et al., 2020). The energy improvement produced electric cars, which could increase the cost of electricity and consumers driving (Safarzyńska and Van Den Bergh, 2018), leading to REs.
In the energy-environmental dimension, GHG emissions were considered in different scenarios of the supply chain that could lead to possible RE (Skelton et al., 2020). Also, autonomous vehicles use more efficient technology and energy to minimise emissions while neglecting the overuse by consumers that could produce REs (Marletto, 2018).
Regarding the economic-environmental dimension, RE could arise from an environmentally friendly production process that could spur higher demand (Abdoli and Kianian, 2021). The purchase of hybrid electric vehicles generates more driving and, consequently, a direct RE (Hamamoto, 2018). Thus, in this case, the eco-social perspective about the use of vehicles (e.g., autonomous vehicles) is the main cause of RE (Martin, 2019).
In the environmental dimension, life cycle assessment (LCA) was used to identify targets for avoiding RE caused by GHG emissions (Bey et al., 2018), which are also caused during car-sharing use (Amatuni et al., 2020).
During the SLR analysis, different research gaps emerged from the selected contributions. Various scenarios of RE generated by new technologies do not consider the negative environmental consequences, limiting the expected reduction of the imposed environmental impact of a car (Abdoli and Kianian, 2021). Also, digital systems that could

avoid possible RE don't include the effects in the social and economic dimensions (Bey et al., 2018; Martin, 2019). Furthermore, new driving systems must be integrated into urban mobility (Marletto, 2018). In urban mobility, consumer perception and behaviour determine whether to adopt these new vehicles, assessing the emissions generated by technological improvements (Hamamoto, 2018; Safarzyńska and Van Den Bergh, 2018). LCA is a static approach to evaluating the social dynamic, that needs to incorporate possible techniques to account for RE (Amatuni et al., 2020).

The interviews were conducted with three different automotive companies. The interviewees involved belong to different areas of companies A, B, and C: mechanical, environmental, and power departments. Company A has followed new recyclability legislation to develop mechanical parts for more than 20 years. Company B has created a new department (i.e., the Environmental Product Department) to implement sustainability in their projects. Company C was still working to move towards sustainability in their product components.

Table 2: Selected contributions analysis (Legenda: Eco.= Economic; Ene.= Energetic; Env.= Environmental)

Ref.	RE-related content	Factor from CE-RE dimensions	Research gap	RE dimension		
				Eco.	Ene.	Env.
(Abdoli and Kianian, 2021)	RE is evaluated on transmission gears within the automotive sector due to the environmentally friendly image of products, which may spur heightened demand, offsetting anticipated reductions in environmental impact.	Innovative and sustainable circular product (PLM)	New process technologies with efficiency in resources impact on product quality outcomes and costs without considering the environmental consequences.	X		X
(Greene et al., 2020)	Fuel improvements saved approximately 2 trillion gallons of gasoline. These were attributed to both gasoline price increases and fuel economy and greenhouse gas (GhG) standards, due to price increases, standards, and the role of RE.	Economic and strategic drivers (Drivers)	Not providing a comprehensive assessment of social costs and benefits.	X	X	
(Amatuni et al., 2020)	A comprehensive model was proposed to estimate the reduction in total annual mobility-related GhG emissions caused by business-to-consumer car-sharing participation, assessing the modal shift effects and shared vehicle lifetime effects.	Life cycle pattern (PLM)	The LCA-based approach is static and operates with average values, potentially overlooking dynamic changes in the socio-transportation system.			X
(Skelton et al., 2020)	The GEM-E3 is a model to calculate the magnitude of GhG emissions that cause RE across a range of efficiency scenarios in the automotive sector supply chain. There is a greater risk of RE for emissions abatement strategies to save embodied emissions.	Circular consumption (Socio-economic aspects)	Surpluses could minimize RE.		X	X
(Hamamoto, 2018)	RE was caused by the purchase of hybrid electric vehicles, which prioritise fuel economy, leading to an uptick in annual mileage per household, which could potentially counterbalance additional costs through fuel savings.	Sustainable purchase intention (Socio-economic aspects)	Study consumer perceptions and their environmental implications, and the relation between hybrid electric vehicle adoption and emissions.	X		X
(Martin, 2019)	Eco-social parameters for the emergence of autonomous vehicles were analysed, with a focus on their potential impacts on social justice and environmental sustainability due to their evolving politics of deployment, which could cause REs.	Motivational factors (Drivers)	The potential for digital system failures raises concerns about security requirements inhibiting mass deployment.	X		X
(Marletto, 2018)	The integration of autonomous vehicle technology into urban mobility systems will significantly determine safety considerations and user behaviours. The effects of automated driving on urban mobility don't consider any type of RE.	Economic, environmental, social and institutional actions (Drivers)	Limited attention is given to how the integration of automated driving technology affects the societal function of urban mobility and its future diffusion.		X	X

(Safarzyńska and Van Den Bergh, 2018)	The impact of incorporating realistic consumer behaviours and technological changes in electricity generation on estimates of emissions from cars was analysed, assessing the interdependence between the car industry and electricity generation (e.g., electric cars).	Consumers' behaviour (Socio-economic aspects)	Emissions from passenger cars and consumer behaviour were underestimated. The impact of technological changes in electricity generation on the rate of adoption of electric vehicles remains lacking.	X	X	
(Bey et al., 2018)	The 'Sustainability Cone' framework helps to define environmental targets to plan products and production systems holistically in line with sustainability requirements, avoiding suboptimization of the RE.	Organisational and financial drivers (Drivers)	Existing sustainability frameworks in manufacturing often lack a comprehensive top-down approach, prioritising only environmental concerns and not economic and social dimensions.			X

From the interviews, it emerged that companies A and B adopted circular strategies in their processes. Company A is developing new technologies to completely recover the components from their products. Company B recycles materials to introduce 25% of post-consumer plastics. However, company C didn't implement circular strategies. The benefits achieved through these strategies are different. Company A is able to anticipate the regulation and provide something on the market that complies with it, monitoring these results with LCA-based key performance indicators (KPIs). Company B has the purpose of increasing the quantity of closed loop plastics in their cars, partially through mechanical recycling and chemical recycling. They assess these results with a specific KPI, which represents the percentage of recycled plastic out of the total plastic used in a car. Finally, even though Company C did not implement CE in their processes, they aim to achieve benefits by minimising the use of raw materials through repair and product dismantling. Company C introduced an internal sustainability KPI to certify its CO_2 neutrality.
In addition, only companies A and B presented some negative effects due to the implementation of circular strategies. Company A revealed a cost impact for the new technology used in the additional function (e.g., disassembly). Company B presented difficulties in validating these new recycled materials and a higher load of technical or feasibility tests.

In conclusion, the SLR revealed that in the automotive industry, a RE occurs but isn't linked to the implementation of circular practices. RE referred only to energy savings, specific system components (e.g., gear transmission), consumer behaviour on purchase, and choosing sustainable vehicles. On the other hand, the interviews reported that no company knows the RE of CE, but they recognised different negative consequences due to the implementation of circular strategies.

4. Discussions

The results obtained through the theoretical and practical investigation allowed to explore RE in the automotive industry.
Seven papers out of nine referred to the environmental dimension of RE. They studied how the GHG emissions produced by cars are negative for the environment, even if new solutions are implemented to achieve energy efficiency. Nevertheless, the energy efficiency improvement represented by electric cars and hybrid electric cars could cause a RE due to increased consumer driving.
The environmental dimension is linked to economics for three contributions and to energy for two. In the economic and environmental dimensions, the negative effects on the environment were produced due to the high purchase of hybrid electric vehicles by consumers. They were driven by an ecological sense of social justice due to energy prices being reduced by the implementation of new technologies. Regarding the energy and environmental dimensions, energy efficiency leads to saving energy and reducing emissions, but it could cause different types of RE that ought to be evaluated by level of negative impact.
In the energy-economy dimension, the close relation between energy savings and price reductions has been studied. Energy efficiency has led to the production of electric cars, which influences the purchasing behaviour of consumers.
In summary, all the selected contributions analysed different types of RE generated only by energy efficiency and producing environmental and economic effects in the automotive industry. In literature, RE of CE could be caused by efficiency improvements due to the implementation of circular strategies (Zink and Geyer, 2017). In the electronics sector, reusing and recycling smartphones could cause a RE due to the imperfect substitution, as they may present an inferior quality or be less desirable to consumers (Makov and Font Vivanco, 2018). In the textile industry, the recycling of clothes could generate RE due to substitution (Siderius and Poldner, 2021). These negative consequences are caused by the CE practices implemented to reduce the use of raw materials. Furthermore, through these studies, the role of a consumer that could generate an RE has emerged. In fact, consumers are willing to buy sustainable, reconditioned, or environmentally positive products (e.g., electric cars).
Several circular strategies have been implemented by car manufacturers and providers in the automotive industry, as the interviews revealed, pushed by new legislation and regulation. In fact, companies are more focused on following new regulations and changing their processes according to them. Indeed, new regulations and legislation represent the drivers that pushed companies to move from a linear to a circular process.
The circular strategies implemented were to recover parts of the component and recycle plastic in cars to realise new products in a circular process. To evaluate the benefits

achieved through these strategies, the companies are obliged to monitor the results using some KPIs. They used the LCA method to determine the amount of recycled plastic in the total plastic used in developing the new car and the level of CO_2 needed to reach neutrality. The circular strategies adopted by companies led to negative consequences: a high cost to change from a linear to a circular process and difficulties in certifying and validating the use of recycled materials while developing new products. None of the companies interviewed mentioned how improving the effectiveness of recycled and recovered materials could generate a type of RE.

These findings represented a lack of awareness of the possible type of RE that could occur in the long run, thereby subsequently limiting the circular benefits being pursued. This lack of awareness arose through the theoretical and practical investigation conducted. Indeed, neither of these investigations presents RE caused by CE practices, and the negative effects detected by the company are economic or due to the legislation.

4.1 Main contributions

This research provides several contributions to both knowledge and practice. First, the SLR categorised and defined what RE is and how it occurs in the automotive industry. The main dimensions (i.e., economic, energy, and environment) in which RE occurs and what causes it, in particular energy efficiency, were identified. The interviews offered a practical overview of the adoption of circular strategies by companies in the automotive industry. In essence, the focus is on satisfying new regulations imposed by policy, such as the reduction of GHG emissions (Bergek and Berggren, 2014) and the introduction of digital product passport. These findings could influence researchers' attention to areas where solutions or recommendations should be developed to support these regulations. Additionally, studying these practices can provide insights to practitioners in the automotive or different industries about the regulatory dynamics, the main challenges to tackle, the opportunities for innovation during the adoption of circular strategies, as well as where and how negative consequences might occur when adopting CE practices to prevent and avoid them.

This research offers managerial implications. It raised awareness about the negative consequences caused by the implementation of circular strategies in the production process of new products. These negative effects could be economic or a challenge in integrating the recycled material. At the same time, this study offered insights about the different types of RE in the automotive industry, which could lead to price reductions for products but also limit the benefits achievable with the adoption of CE strategies.

Lastly, this study contributed to discussing potential policy interventions to implement CE in the automative industry and to addressing possible REs of CE to maximise environmental, social, and economic benefits. One of the main recommendations for policymakers is to establish precise and consolidated rules in the long run to allow companies to effectively plan their activities in implementing and monitoring their CE practices and initiatives.

5. Conclusions

The objective of this research was to investigate the level of awareness and knowledge of the possible occurrence of different types of RE within CE in the automotive industry through theoretical and practical analysis. To address this purpose, a SLR was conducted to identify the possible types of RE that could occur in the automotive industry from a theoretical point of view. In fact, a systematic organization of the knowledge of RE in the context of the automotive industry was provided. For the empirical investigation, a series of semi-structured interviews have been conducted with different experts operating in automotive companies. Indeed, the interviews revealed the level of awareness about the possible negative consequences caused by the implementation of circular strategies. The results obtained through these two different investigations show a lack of awareness in this specific industry about the RE of CE practices.

This research also presented some limitations. It focused only on one sector (i.e., automotive) neglecting other relevant ones (e.g., WEEE, textile). The number of documents collected through the SLR was restricted due to the focus on the automotive industry. Also, a limited number of interviews were conducted. In addition, the interviewees belonged to different departments, and none of them were closely related to the sustainable department. This offered a wider perspective on the adoption of CE practices in the overall processes of the organizations involved, but a more restricted insight into the level of circularity achieved by the companies in question.

Future research should focus on increasing knowledge and awareness about the possible occurrence of different types of RE within the implementation of CE practices, starting from automotive companies. Future developments should provide practical application studies to deeper analyse the adoption of CE practices within processes to identify related benefits and possible RE. Lastly, based on the feedback from the interviews, gaps about the use of indicators to measure the benefits achieved through the implementation of circular strategies emerged. Consequently, a methodology to assess and measure the CE benefits achieved and the possible occurrence of RE should be developed.

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