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Circular Economy Adoption in Manufacturing Firms: Evidence From Germany

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ABSTRACT

This paper analyses Circular Economy (CE) practices adopted by manufacturing firms and explores whether the decision to adopt these practices differs in relation to manufacturing sector, company size, or having Environmental Management Systems (EMS) in place. Empirical data from 1191 German manufacturing firms was used to show that the circular practices companies adopt most are framed mainly within Recovery Field of Action (FA), followed by Distribution and Use. Findings highlight differences between sectors and point to a correlation between company size or having an EMS and a higher level of CE adoption, emphasising the need to tailor CE strategies to specific industrial sectors and company size, and highlighting the role EMS plays in facilitating the adoption of CE.

1 | Introduction

"Squaring the Circle: Policies from Europe's CE Transition" (World Bank 2022) was The World Bank's first comprehensive report on the Circular Economy (CE) in the European Union (EU). The report states that EU countries lead the world in promoting the transition towards CE, having made it a central focus of their growth strategy in an ambitious policy reform.

However, the transition to full CE requires urgent and comprehensive action from all sections of society. The way products are designed, manufactured, used and managed at the end of their useful life is highly significant and has ramifications in a number of areas, including the demand on natural resources, the impact on climate change and the amount of waste generated. Thus, regulators, businesses and consumers, have an important role to play in advancing circular solutions.

Although the European private sector is emerging as a driver of CE, circular business models remain limited (average market share is estimated at only 5–10%). Currently, recycled materials account for only 8.6% of raw materials, and the share of remanufactured products compared to newly manufactured products is only 1.9% (World Bank 2022). This clearly demonstrates the need to continue transforming the current production model, making it more sustainable and responsible by heightening the uptake of CE practices, which provide an alternative to the traditional linear economic model, characterised by the cycle of extraction, production, consumption and disposal.

Adopting circular practices is vital for business sectors with a high environmental impact. In this context, the role of the manufacturing sector is key as it is one of the four activities making up the European industrial sector: 1) manufacturing; 2) mining and quarrying; 3) electric, gas steam and air conditioning

This paper analyses Circular Economy practices adopted by manufacturing firms and explores whether adopting these practices differ according to manufacturing sector, company size, or having Environmental Management Systems in place. The results, based on German manufacturing survey, show that the circular practices companies most commonly adopt are mainly framed in Recovery Field of Action and highlight differences between sectors, company size or having an EMS.

supply; and 4) water supply, sewerage, waste management and remediation activities. In 2019, the manufacturing industry was the largest and most important of these four activities, accounting for approximately 85% of industrial added value in the EU and 90% of industrial employment. (Circular Economy Foundation 2022). This demonstrates both the significance of the manufacturing sector at a European level, and the interest in analysing the extent to which the industry is adopting the circular model. Using this data to measure and track circular performance across companies will enable actors to set goals, peer review, as well as measuring and benchmarking performance.

Ideally, businesses of all sizes should adopt circular practices; however, current models for adopting a Circular Economy (CE) primarily target large companies (Howard et al. 2022). Small and medium-sized enterprises (SMEs), on the other hand, face distinct challenges related to factors such as limited access to investments and differences in corporate structure. These circumstances frequently result in reduced investment capacity, particularly in the realms of product design and research and development activities. Moreover, SMEs often face greater challenges in executing projects aimed at enhancing the efficient use of production resources and undertaking internationalization initiatives (Ministerio de Economía Industria y Competitividad 2018).

Another consideration in the transition towards a more circular production model is the role played by Environmental Management Systems (EMS). Institutions, governments and researchers alike have highlighted the importance of EMS as it is instrumental in supporting circular transformation through environmental policy (Barón Dorado, Giménez Leal, and de Castro Vila 2022; British Standards Institution 2017; European Commission 2017; Evans et al. 2015). Companies aiming to become more sustainable can monitor and improve their environmental performance through their EMS, which requires them to assess, manage and improve their environmental impact, thus ensuring excellent environmental performance consistent with their environmental policy. The European Commission emphasises that EMS contribute implicitly to the CE model approach through the required life cycle analysis of products and services, which guides companies through the transition to CE (European Commission 2017). Thus, exploring the relationship between EMS and adopting circular practices is also important for practitioners and regulators.

Based on the above, the main objective of this paper is to analyse which CE practices are being adopted by manufacturing companies and whether these practices are adopted differently according to sector, company size and whether the company has an EMS in place (or not).

The theoretical lenses used in this investigation for approach to empirical reality are the Practice-Based View (PBV) theory of the firm. PBV is a framework in organizational theory that focuses on understanding organizations through the lens of practices. PBV recognizes practices as activities that different types of manufacturing companies can perform, and are susceptible to imitation and transfer (Bromiley and Rau 2014). PBV can be used to explain deviations and differences in performance among companies. Through its application, scholars are guided to study the emerging implications and gaps of CE practices' implementation on companies' sustainability performance (Mora-Contreras et al. 2023).

The remainder of the paper is structured as follows. Section 2 sets out the theoretical framework of the study, including the research questions. Section 3 describes the methodology of the empirical study. Section 4 presents the findings, and Section 5 develops the discussion on the findings. The paper concludes with a summary of the main conclusions and implications.

2 | Theory Development and Research Questions

In line with the aims of the study, this section introduces the concept of CE and reviews the literature related to the adoption of circular practices within companies. The role EMS plays in the transition towards the circular model is also examined, and the research questions posed.

In simple terms, the concept of CE can be defined as an economic model based on efficient and resilient production and consumption systems that preserve all types of resources by optimising their value within a continuous closed loop. However, CE is not a simple concept. Proof of this is that some scholars understand CE as a model focused on a closed-loop material flow (Kama 2015; Li et al. 2010; Yuan, Bi, and Moriguichi 2006), while others focus on economic aspects, defining it as an economy integrated with resources, environmental factors and territoriality (Andersen 2007; Ellen MacArthur Foundation and Granta Design 2015). Although there are a multitude of definitions for CE (Ellen MacArthur Foundation 2017; Murray, Skene, and Haynes 2017; Prieto-Sandoval, Jaca, and Ormazabal 2018), all agree that it as a lever for change that can help address strategic growth challenges, bringing economic, environmental and social value. Most definitions also see CE as a new economic paradigm, involving rethinking ways of producing and consuming.

Companies need to redesign their processes and products from the ground up, and consumers need to make choices that encourage circularity. Governments also have a key role to play as they can set the framework for action at the national level by introducing ambitious policies that enable and promote circular transformations. Taxation can also be an important instrument to create the right incentives to guide the behaviour of market actors, and regulations banning practices such as plastic bag manufacturing, or rules on mandatory minimum requirements (e.g. recycled content in packaging) are also key.

The CE has strong synergies with the EU's commitments on sustainability, particularly in order to achieve Sustainable Development Goal SDG12 'Responsible consumption and production'. Furthermore, UN Reports on SDGs (United Nations 2021) and authors such as Leal Filho et al. (2023) argue that more decisive action is required to overcome significant sustainability challenges such as climate catastrophe and resource scarcity. On 11 March 2020, the European Commission adopted a new Circular Economy Action Plan, which is a cornerstone of Europe's new agenda for sustainable growth, the European Green Deal. The Action Plan announced initiatives across the entire life cycle of products. It targets areas such as product design and circular economy processes, thus fostering sustainable consumption and ensuring that the resources used are kept in the EU economy for as long as possible. The Action Plan has introduced legislative and non-legislative measures that target areas where action at EU level brings real added value (European Commission 2023a).

On 5 January 2023, the Corporate Sustainability Reporting Directive was introduced in response to the recent, rapid rise in demand for information on this topic. The directive has modernised and strengthened the rules surrounding companies' social and environmental reporting, enabling access to reliable and comparable data as a broader set of large companies and listed SMEs will now be required to report on sustainability. These new rules will also ensure that investors and other stakeholders have access to the information they need to assess the impact companies have on people and the environment, and the financial risks and opportunities arising from climate change and other sustainability issues. In addition, companies will lower their reporting costs in the medium to long term as the information provided will be standardised (European Commission 2023b).

The circular model evidently affects many actors, so it is useful to analyse it at different levels. 'Macro' level includes the national and supranational level, where the government works on promoting recycling and a circularity-oriented society, including cities and states. The intermediate 'meso' level deals with local experiences of industrial symbiosis and eco-parks, and 'micro' level refers to companies and organizations, with CE objectives mainly focusing on making production more environmentally sustainable (Kirchherr, Reike, and Hekkert 2017; Mathews and Tan 2011; Saidani et al. 2017).

This study analyses manufacturing companies' adoption of circular practices within the micro level, where companies play an important role in the transition towards CE, as their activities have a significant impact on the environment (Barreiro-Gen and Lozano 2020; Kravchenko, Pigosso, and McAloone 2019; Lieder and Rashid 2016).

According to the PBV theory (Bromiley and Rau 2014), the analysis focuses on specific CE practices and consider that they are situated within specific contexts. Linking the concepts is based on two key aspects of PBV theory: (1) Focus on everyday actions, routines, and practices that individuals and groups engage in within an organization, so they are seen as the building blocks of organizational behaviour and performance and (2) the effectiveness and nature of practices can vary depending on the organizational environment, culture, and external factors. This means that context differences lead to different adoption behaviour.

2.1 | The Adoption of CE Practices in Companies

CE practices adopted by companies include using renewable energies and materials and extending the useful life of products through maintenance and eco-design. Other practices include eliminating waste in supply chains, keeping components and materials in closed loops through remanufacturing and recycling, replacing old materials with new materials of renewable origin, and establishing synergies of exchange and exploitation between industries (industrial symbiosis) through the use of new technologies. However, for a successful transition to a more sustainable circular model, these changes should be made without companies having to compromise their efficiency and growth rate.

The new paradigm posed by the circular model should be seen by companies as an opportunity to innovate and be more competitive, rather than simply being more sustainable (Mura, Longo, and Zanni 2020; Thorley, Garza-Reyes, and Anosike 2019). This also means addressing the circular advantage from the point of view of customers (Accenture Strategy 2015) and implementing new circular business models such as servitisation, shared-use platforms, product life extension and resource recovery (Lacy et al. 2015). Beyond enforcing regulations, another good way to encourage circular practices through government bodies (Hu, He, and Poustie 2018; Testa, Boiral, and Iraldo 2018) is to offer financial support for incentives encouraging investment in more sustainable alternatives (e.g. tax reductions on circular materials) and to offer loans and grants for R&D (Fischer and Pascucci 2017; Fletcher, Hooper, and Dunk 2018; Ghisellini et al. 2018).

To monitor the extent of circularity implementation, the European Environment Agency (2016) proposed measuring the life cycle of products and/or systems, i.e., the design, production, consumption, end-of-life stages, attempting to group these specific circularity actions into key characteristics. Some authors have also proposed models to measure circularity practices in organizations at both national and regional level (Masi, Day, and Godsell 2017; Mura, Longo, and Zanni 2020), and attempted to classify them into processes (Rizos et al. 2016), levels (Aranda-Usón et al. 2020), Fields of Action (FA) (Prieto-Sandoval et al. 2019; Prieto-Sandoval et al. 2018), dimensions (L. M. Fonseca et al. 2018) or factors (Garza-Reyes et al. 2019).

Many scholars have analysed the challenges companies face when trying to adopt more circular practices (Agyemang et al. 2019; Geng and Doberstein 2008; Mura, Longo, and Zanni 2020; Ormazabal et al. 2018; Shi et al. 2008). These challenges are similar in many cases, although differences were detected according to the geographical area they operate, or the sector they belong to (Bassi and Dias 2019; Klein, Ramos, and Deutz 2021).

To group the various circular practices, this study follows the model developed by Prieto-Sandoval, Ormazabal et al. (2018), which defines CE as a cyclical flow that involves extracting, transforming, distributing, using and recovering materials and energy from products and services. This model aims to assess circularity at a micro level through the five Fields of Action that span a product's life cycle from the initial extraction of raw materials to recovery of materials at the end of their useful life: Take, Make, Distribute, Use and Recover.

We have previously pointed out that the concept of CE can also be approached from the scope of an economy integrated with resources, environmental factors and territoriality (Andersen 2007; Ellen MacArthur Foundation 2015), i.e., under the concept of Industrial Symbiosis (IS). Following Chertow, this term engages "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, water and/or by-products" (Chertow 2000, p.313). IS can be understood as a form of intermediation bringing companies together in innovative collaborations. Local or wider cooperation in IS can reduce the need for virgin raw materials and depositing waste, thus closing the materials loop, which is a key feature of CE and a driver of green growth and eco-innovative solutions. IS can also reduce emissions and energy use and create new revenue streams (Elia et al., 2020; Mallawaarachchi et al. 2020; Marchi, Zanoni, and Zavanella 2017; Rincón-Moreno et al. 2021; Wen and Meng 2015). Therefore, the present study also views business initiatives related to IS as circular practices, considering them the sixth FA.

Several studies analyse micro level CE adoption in different countries, sectors, and company sizes, but failed to reach a consensus on the classification and measurement of the circular practices examined (Barón, de Castro, and Giménez 2020), or whether adoption differs according to environment, a topic still under debate among practitioners and academics (Mora-Contreras et al. 2023).

A literature review was conducted to identify key studies related to the adoption of circularity practices across various countries and sectors. In this context, 'practice' refers to activities undertaken by multiple companies in the public domain (Bromiley and Rau 2014) and therefore open to transfer between companies.

The search criteria included keywords such as 'circular economy', 'practices', 'adoption', 'firm', 'industry' and 'manufacturing' using the SCOPUS search engine. Searches centred on the 'Business' and 'Environment' fields and peer-reviewed scientific articles spanning the period up to 2023. A total of 141 results were obtained, and after applying the exclusion criteria to filter out non-empirical studies or those belonging to other research fields, a final set of 28 articles was identified (see Table 1).

The most significant manufacturing companies in terms of circular potential were the Agri-food and Chemical sectors (tech4goodcongress 2019). Several studies point to FAs Take and Make as the areas where companies have the greatest impact in order to contribute to greater circularity (L. M. Fonseca et al. 2018; Jaime Ferrer (Coord.) 2021). Other research, however, suggests that the focus should be on Recover (Prieto-Sandoval et al. 2018). Several studies conclude that companies focus mainly on efficient energy use and reducing raw materials (Elia, Gnoni, and Tornese 2020; L. M. Fonseca et al. 2018), but others found that the practices most adopted are renewable resources and waste recovery (Barón Dorado, Giménez Leal, and de Castro Vila 2022; Jaime Ferrer (Coord.) 2021). Yet another study points to eco-design as the main driver of circular transformation practices (Barón, de Castro, and Giménez 2020; Mora-Contreras et al. 2023). The least adopted practices, on the other hand, are the extension of useful life (Make), shared-use platforms (IS) and servitisation (Use) (Accenture Strategy 2015; L. M. Fonseca et al. 2018). In line with Acerbi, Sassanelli, and Taisch (2022) Barón Dorado, Giménez Leal, and de Castro Vila (2022) point to a widespread lack of circular practices among companies, or actions related to extending product lifetime, reusing, refurbishing or remanufacturing.

To further explore and deepen knowledge about the adoption of CE practices in manufacturing companies in FA, objective and quantitative data was provided to address the following research questions:

RQ1. *What FAs are manufacturing companies working on most?*

RQ2. *What is the correlation between the activity sector and a higher level of adoption of CE initiatives in manufacturing companies?*

Barón Dorado, Giménez Leal, and de Castro Vila (2022) pointed out that there is no variation in the adoption of circular practices according to company size; however, several studies demonstrate that this is not the case (Bassi and Dias 2019; Howard et al. 2022). These studies highlight the difficulty SMEs face when adopting circular practices compared to large companies, pointing out that the main weaknesses for SMEs are lack of staff training, access to advice, technological support and access to financing. Thus, the third research question is posed:

RQ3. *What is the correlation between company size and a higher level of adoption of CE initiatives in manufacturing companies?*

2.2 | Environmental Management Systems

During the 1990s, so-called Environmental Management Systems (EMS) were developed as instruments for companies to voluntarily achieve a high level of environmental protection within the framework of sustainable development. Numerous definitions of EMS were proposed, but the one proposed by the International Organization for Standardization (ISO) stands out: The part of the general management system used to manage environmental aspects, fulfil compliance obligations and address risks and opportunities (International Organization for Standardization-ISO 2015). This includes the organizational structure, activity planning, responsibilities, practices, procedures, processes and resources for developing, implementing, carrying out, reviewing and keeping the environmental policy up to date.

EMS can help companies to: (i) identify and control environmental aspects, impacts and risks relevant to the organization; (ii) establish short, medium and long-term objectives for the company's environmental performance, analysing the cost–benefit balance for the organization and its stakeholders; (iii) determine what resources are required to successfully achieve the predetermined objectives, assigning responsibilities in each case; (iv) define and document the various tasks and operations, responsibilities, authority and procedures to ensure that all workers act on a day-to-day basis, minimizing or eliminating any negative impacts the company has on the environment; (v) improve the organization's communication channels, training people to assume their responsibilities; and (vi) measure environmental performance on a day-to-day basis to see if the predetermined objectives are achieved, modifying when deemed necessary.

EMS can differ from one organization to another. Nevertheless, there are a number of basic elements common to any system such as the Environmental Policy. This policy expresses the management's commitment to proper environmental management, or the Action Plan, which describes the measures the company will take in the coming years. Another important element is the

TABLE 1 | Studies related to adoption of circular practices.

Authors	Country (Region)	No. firms/sector	Methods
Barco and van Hoof 2022	Colombia	1/Leather industry	Case study
Khan et al. 2022	Poland, Romania, Ukraine	213/Automotive industry	Survey
Rodríguez-González et al. 2022	Mexico	460/Automotive industry	Panel discussion/survey
Pinheiro et al. 2022	Brazil	142/Electric–electronic, equipment industry	Survey
Yu, Khan, and Umar 2022 Z	China	286/Automotive industry	Survey
Barón, de Castro, and Giménez 2020	Spain	85/Manufacturing	Survey
Bag et al. 2021	South Africa	219/Automotive industry	Survey
Brydges 2021	Sweden	19/Fashion industry	Interview
Colucci and Vecchi 2021	Italy	4/Fashion industry	Case study
Do et al. 2021	Germany	4/Food industry	Multiple-case study
Gandolfo and Lupi 2021	Italy	1/Paper industry	Case study
Saha, Dey, and Papagiannaki 2020	Bangladesh, Vietnam, India	114/Textile and clothing industry	Survey
Aranda-Usón et al. 2020	Spain (Aragón)	52/Industry and services	Interview
Barón, de Castro, and Giménez 2020	Spain (Catalonia)	31(SME)/Industry	EMAS statements
Barreiro-Gen and Lozano 2020	GRI Data base	256	Survey
Dey et al. 2020	UK	130 (SME)/Manufacturing	Case study/survey/focus group
Elia, Gnoni, and Tornese 2020	Ellen MacArthur F. Data base	96	Case study
Mura, Longo, and Zanni 2020	Italy	254 (SME)/Manufacturing and others	Interview/survey/focus group
Rincón-Moreno 2020	Spain	17 SME	Survey/interview
Trigkas et al. 2020	Greece	32 leading companies	Survey
Bassi and Dias 2019	EU	441 SME/manufacturing, services	Interview
Janik and Ryszko 2019	Poland	66	EMAS statements
Fonseca et al. 2018	Portugal	99	Survey
Botezat et al. 2018	Romania	98/Industry	Survey
Oncioiu et al. 2018	Romania	384 (SME)/industry and services	Survey
Ormazabal et al. 2018	Spain (Basque Country)	95	Survey
Ormazabal et al. 2016	Spain (Basque Country)	17 (SME)/industry	Case study

environmental audit, which verifies the adequacy and effectiveness of EMS implementation and operation.

In Europe, two models set the guidelines for developing an EMS: The ISO14001 Standard and the Environmental Management and Audit Scheme (EMAS). ISO 14001 can be audited and certified by independent external certification bodies who assess whether the applicable EMS complies with ISO 14001 requirements and achieves the intended results by performing a third-party audit (L. Fonseca et al. 2022). ISO 14001 is one of the most widely adopted ISO international management system standards, with 529,853 certificates worldwide (ISO 2019). EMAS was established by the European Commission through the dedicated EMAS Regulation, and is an instrument for evaluating, reporting and improving the environmental performance of organizations, enabling them to adhere voluntarily to a community system. Both EMS models emphasise a life-cycle perspective of products and services, which is essential for companies if they want to adopt circular initiatives.

Implementing EMS compels a company to identify key performance indicators of its environmental impacts, thereby generating quantifiable and objective data that can aid decision-making. These indicators enable the investigation of aspects such as resource efficiency, changes in processes, the search for less polluting materials and other actions driving innovation (O. Khan, Daddi, and Iraldo 2020). In the case of companies with EMS based on the EMAS model, the environmental statement facilitates transparency with stakeholders, highlighting the actions taken to move towards a more circular production model.

Based on the above, some authors claim that EMS contribute to the goal of achieving corporate sustainability and reducing the environmental impact of their products and processes (Sebhatu and Enquist 2007). Other authors claim that EMS companies enjoy a strategic advantage over their competitors, enabling them to align their operations with CE principles more easily (Barón Dorado, Giménez Leal, and de Castro Vila 2022; L. M. Fonseca et al. 2018; Jain, Panda, and Choudhary 2020; Zhu, Cordeiro, and Sarkis 2013). This stance is also advocated by institutions such as the European Commission through its Pact for a Circular Economy (European Commission 2015), with guidelines aimed at increasing innovation and the overall efficiency of production processes through measures such as EMS implementation. Given this drive towards EMS adoption by institutions, the uptake of certifiable EMS (Ma et al. 2021) among companies has been remarkable in many countries (Chiarini 2017; Daddi, Iraldo, and Testa 2015; Matuszak-Flejszman, Szyszka, and Jóhannsdóttir 2019). Against this background, other studies highlighting the strengths and weaknesses of these management systems have been published (Barón Dorado, Giménez Leal, and de Castro Vila 2022; Boiral et al. 2018; Daddi et al. 2016; Heras-Saizarbitoria, Arana, and Boiral 2016; Merli and Preziosi 2018; Testa et al. 2016; Testa, Boiral, and Iraldo 2018), some questioning the contribution to corporate environmental performance (Heras-Saizarbitoria et al. 2020).

Thus, to help clarify the role of EMS in the transition towards a more circular production model, this study proposes the fourth research question.

RQ4. *What is the correlation between EMS implementation and a higher level of adoption of CE initiatives in manufacturing companies?*

3 | Methods

3.1 | Study Sample

The empirical data used in this study were drawn from the German extract of the 2018 *European Manufacturing Survey*, which investigates technological and non-technological innovation in European industries. This survey was first launched in 1993 (Lay and Maloca 2004) to systematically observe production companies regarding their product, process, service and organizational innovations, and is currently conducted every three years. The survey addresses manufacturing firms with 20 or more employees from all manufacturing sectors (NACE Rev. 2, 10-33) in a country. The data from this broad empirical survey were used in several firm-level studies (e.g. Bikfalvi, Jäger, and Lay 2014; Dachs and Zahradnik 2022; Kinkel et al. 2011; Kirner, Som, and Jäger 2015; Lerch et al. 2022). In 2018, the *European Manufacturing Survey* received 3985 responses from 14 European countries (Austria, Croatia, Denmark, Germany, Lithuania, Netherlands, Norway, Portugal, Serbia, Slovakia, Slovenia, Spain, Sweden and Switzerland).

This study focuses on data from Germany for several reasons, three of which stand out: First, Germany plays a pivotal role in the EU manufacturing sector, as evidenced by the latest Eurostat data from 2022 (key European company figures - 2022 edition, p32 of the report). These data reveal that Germany holds the EU's largest share of added value and employment within the manufacturing sector. Second, Germany plays a leading role in the adoption of EMS. According to data published by the European Commission on the EMAS website in November 2022, Germany has the second highest number of EMAS companies and the third highest number of in ISO 14001 certified companies. This is significant as this article analyses the relationship between companies' EMS adoption and circular practices. Third, the German business sector is actively encouraged by governmental bodies and business organizations to embrace EMS. Notably, Germany has developed its own EMAS implementation tools, including those employed by the Bavarian Environment Ministry. This proactive approach underscores the nation's commitment to fostering sustainable business practices, making it an ideal focus for our research.

The *German Manufacturing Survey* was extracted from the 2018 *European Manufacturing Survey*. In 2018, 17,305 randomly selected manufacturing firms in Germany were asked to complete a questionnaire, either on paper or online, with 1256 firms returning useable responses. Of these, 1191 companies corresponded to the EMS firm-size inclusion criteria (Jäger and Maloca 2019). The questionnaires were completed by high-level representatives such as production or general managers (CEOs), and the random sample processing followed a strict protocol. On completion of the survey, the data was compared with that of the Federal Statistical Office, revealing that the data set collected is representative of regional distribution and in line with the distribution in data from the German Federal Statistical Office in terms of firm size, class, and industry structure. Successive wave analysis was applied to assess any potential nonresponse bias (Duszynski et al. 2022; Lewis, Hardy, and Snaith 2013; Lin and Schaeffer 1995) and a comparison between firms that responded early in the survey period with those that responded later revealed no relevant differences in key indicators. Table 2 shows the descriptive statistics regarding firm size, sector, and EMS certification.

3.2 | Measurement and Analytical Approach

The *German Manufacturing Survey* asks companies questions about practices or initiatives associated with CE. Several questions on the adoption of circular practices were of interest and have been used for the present study. Table 3 gives an overview of the variables in relation to the FA of the proposed theoretical

TABLE 2 | Sample description.

		# Firms	%
Firm size			
	Small (20–49 employees)	525	44%
	Medium (50–199 employees)	483	41%
	Large (≥200 employees)	183	15%
	Total	*1191*	*100%*
Industrial sector (NACE rev. 2)			
	Electrical & electronic equipment (26, 27)	266	22%
	Machinery & transport equipment (28–30)	249	21%
	Rubber & non-metal products (22, 23)	178	15%
	Metal industry (24, 25)	145	12%
	Agri-food & textile products (10, 11, 13–15)	141	12%
	Other manufacturing sectors (12, 16–21, 31–33)	212	18%
EMS certificate			
	Yes	269	23%
	No	885	77%

model. In total, 21 variables relate to the FA, and the key indicators of CE practices were operationalized based on these. According to the classification, we first measured whether a company is active in one specific FA by assessing if it is using at least one related activity. Consequently, six indicators for the company's engagement in the FA were created, indicating whether the firm is already engaged or not (yet) engaged in the respective FA.

Second, the intensity of engagement in the FA is assessed, i.e., the extent to which a company is engaged in the particular FA. For this purpose, the number of activities was compared to the number of possible activities in the field. As some items relate to product innovation, these percentages were calculated in a way that is sensitive to companies with no product innovation, so they can also reach full engagement in the Make, Use and Recover fields of action. In Table 3, the maximum number of items for each FA is marked as the baseline.

Third, the level of adoption of CE initiatives is measured by classifying the firms according to the number of FAs they are engaged in. This count variable is transformed into an ordinal variable that differentiates between firms with no activity at all or up to two FAs only at the low level, with activity in three or four FAs at medium level, and firms with activities in five, or all five, FAs at a high level of CE adoption.

Furthermore, the German Manufacturing Survey questionnaire included questions on EMS use so it was possible to differentiate between firms that have implemented EMS and firms that have not. Finally, this analysis also relies on basic characteristics of companies using data on firm size, captured as number of employees and sector affiliation.

To address the four research questions of this study, particularly the impact of sector, company size and EMS implementation, bivariate correlations are shown in addition to descriptive information. These correlations were tested using the Kruskal–Wallis Test, given the non-metric character of the variables. Finally, ordinal and multinomial regression models were estimated to test the effect of the use of an EMS on the level of adoption of CE practices while simultaneously controlling for size and sector.

4 | Results

The descriptive analysis shows the 21 CE practices analysed (Figure 1). The practices adopted most are 'Product maintenance and repair services (US4)' (45%) and 'Kinetic and process energy recovery (RV1)' (37%). It is worth noting that all the other practices observed are below 30% adoption. The CE practices least adopted are 'Introduction of recycling/recovery improvements (RV2)' (7%) and 'Products with ease of maintenance or retrofitting (US3)' (7%).

Findings related to the research questions posed are analysed below.

RQ1*: What fields of action are manufacturing companies working on most?*

Combining this information in Figure 2 shows that the majority of manufacturers (55%) are engaged in Use FA, followed by Industrial Symbioses (50%) and Make (47%). Over a third of all firms are active in each of the other FAs. However, to address RQ1, intensity of engagement (right of Figure 2) must be taken into consideration.

TABLE 3 | Circular initiatives in the fields of action model and measurement variables.

Field of action—circular initiative	Measurement variables
TAKE – Incorporating resources from the environment, making more efficient and responsible use of biological and technical resources. This includes the selection of suppliers and materials with environmental criteria as well as certifications and labels.	TK1 – Use of reused and/or recycled raw materials (0) TK2 –Technologies for recycling and reuse of water (0) (Baseline of maximum two possible items)
MAKE – Developing the best technological practices and ecological innovations (eco-innovations) so that both the product/service and the process are carried out in the most sustainable way possible.	MK1 – Specific technology for dealing with recycled raw material (1) MK2 – Implementation of energy management systems (0) MK3 – Implementation of life cycle assessment tools (0) MK4 – Introduction of technological improvements (2) MK5 – Design aimed at extending product lifetime (3) (Baseline of maximum three or five possible items)
DISTRIBUTE – How the product/service is delivered to the customer (traceability and reducing environmental impact). Includes reverse logistics.	DB1 – Cooperation in distribution processes (0) DB2 – Product end-of-life service—reverse logistics (0) (Baseline of maximum two possible items)
USE – Reducing the energy consumption associated with using the product or the efficiency of the product itself (allowing customers to return the product after use or the development of business models where the final consumer is not the owner of the goods).	US1 – Products with reduced energy consumption during use (3) US2 – Products with reduced environmental pollution during use (3) US3 – Products with ease of maintenance or retrofitting (3) US4 – Product maintenance and repair services (0) US5 – Product refurbishment and modernisation services (0) US6 – Product, machinery, or equipment rental services (0) (Baseline of maximum three or six possible items)
RECOVER – Recovering waste as a biological resource that can be returned to the biosphere or as a technical resource that can be reincorporated into an industrial process.	RV1 – Kinetic and process energy recovery (0) RV2 – Introduction of recycling/recovery improvements (3) (Baseline of maximum one or two possible items)
INDUSTRIAL SYMBIOSIS – Establishing synergies of exchange and exploitation between industries with the aim of producing a beneficial relationship for the industries involved (e.g. reusing outflows from a particular industry as raw material for another industry, or putting common services, infrastructures and/or projects into effect).	IS1 – Joint purchasing (0) IS2 – Production cooperation (4) IS3 – Cooperation in service (0) IS4 – R&D cooperation with other companies (0) (Baseline of maximum three or four possible items)

Note: The items are dichotomous variables, differentiating between the following: (0) users and non-users; (1) firms using and not using specific technologies, or not using recycled/reused material in production; (2) firms with product innovation due to environmental improvements and firms with conventional production innovation, or no product innovation at all in the last 3 years; (3) firms with product innovation due to specific environmental improvements and firms with other sustainable product innovation, conventional production innovation or no product innovation at all in the last 3 years. (4) Due to a programming error, the first 135 firms were not asked about Production cooperation (IS2) and no systematic bias was introduced.

The average share of CE practices used within each FA reveals that firms work most intensively in the field of Recover (36%), followed by Use and Distribute (26%). It is noteworthy that Make (19%) has the lowest intensity, despite the fact that manufacturing companies were analysed. In conclusion, a considerable share of firms first began activities in the different FAs; however, the intensity is still quite low.

RQ2: What is the correlation between activity sector and a higher adoption of CE initiatives in manufacturing companies?

Figure 3 provides the first insights into sectoral differences. Company engagement in the various FAs shows considerable differences between sectors, with Use differing the most. Sectors that stand out in Use are Machinery & Transport Equipment (89% of firms engaged) and the Metal industry (86% of firms engaged). These two sectors also show a higher degree of adoption of at least one Industrial Symbiosis practice (63%). The Metal industry also excels in engaging in the field of Distribute (60%). The Rubber & Non-metal sector (53%) is more proactive in Take FA compared to other sectors. The Agri-food & Textile sector stands out as the most proactive sector in Recover FA (55%). Finally, all sectors are at approximately the same level of engagement in circular practices related to the Make FA.

To answer RQ2, Figure 4 shows the level of adoption of CE initiatives, i.e., the variety of FAs implemented by companies in the different sectors. Thus, the Metal industry is the sector most proactive in trying to address circular actions in all the FA. Of these companies, 23% are engaged in five or six of the FAs. Similarly, firms in the Machinery & Transport Equipment sector are also quite proactive, with 20% engaged in five or six of the FAs. Furthermore, only 3% of these companies are not engaged

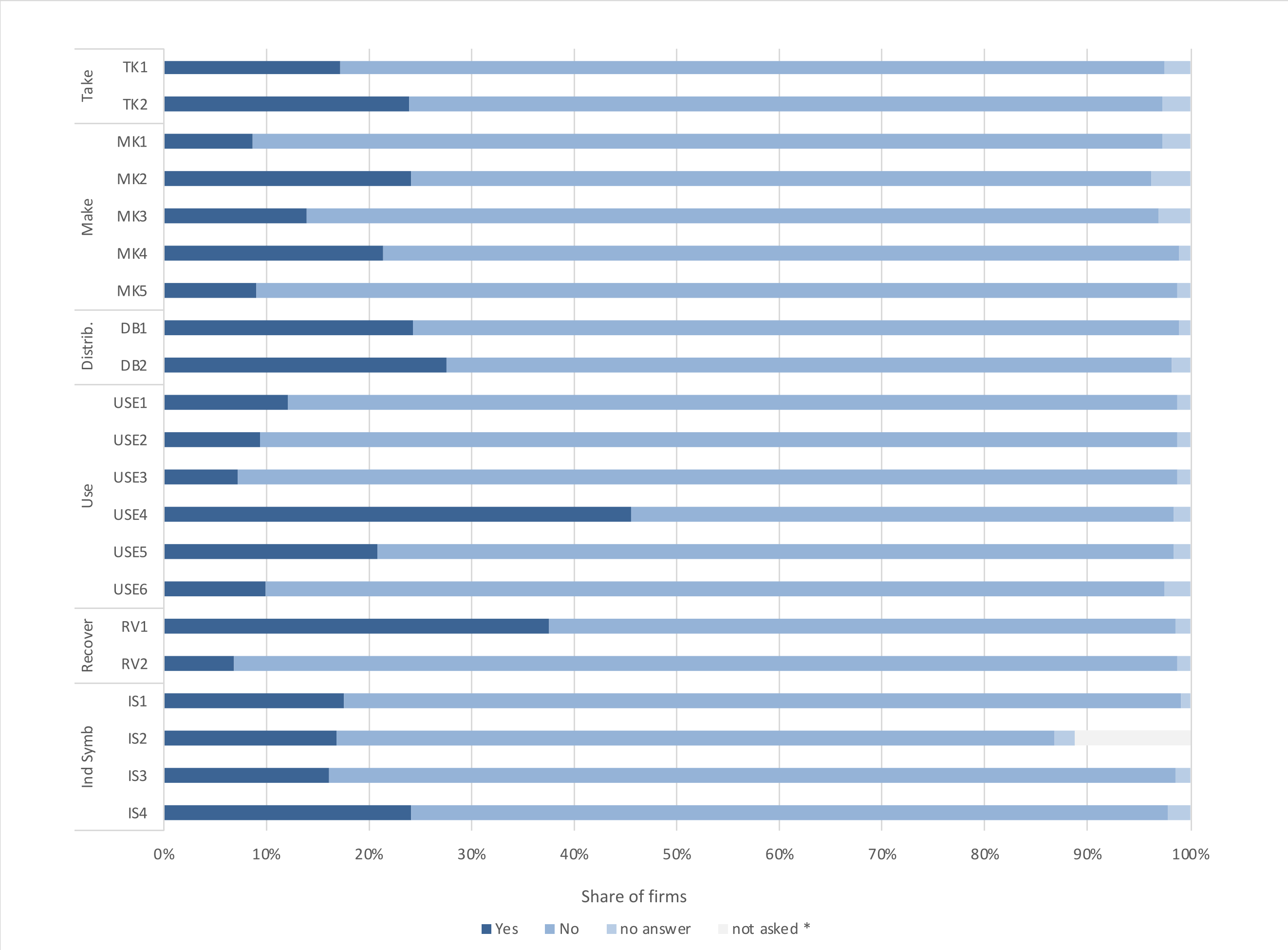

FIGURE 1 | Adoption of CE practices.*Due to technical problems, these firms were unable to address this question.

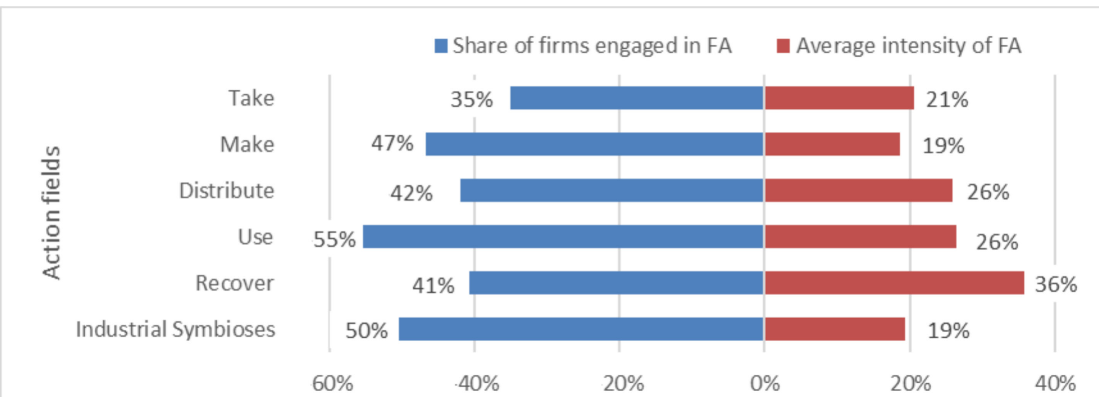

FIGURE 2 | Firms' engagement and intensity of engagement, by FA.

in any FA. The least proactive sector appears to be the electrical and electronics sector, with only 8% engaged in five or six FA, 50% engaged in one or two FAs only, and 10% are not active in any FA whatsoever.

The statistical tests revealed that the correlation between the activity sector and the level of adoption of CE initiatives grouped in the FA is statistically significant. Both the one-way ANOVA tests and the Kruskal–Wallis non-parametric test revealed that levels of adoption differ between sectors ($p < 0.01$). Therefore, the hypothesis that the level of adoption of CE initiatives differ significantly between the studied sectoral groups is supported.

RQ3: What correlation is there between company size and a higher level of adoption of CE initiatives in the manufacturing sector?

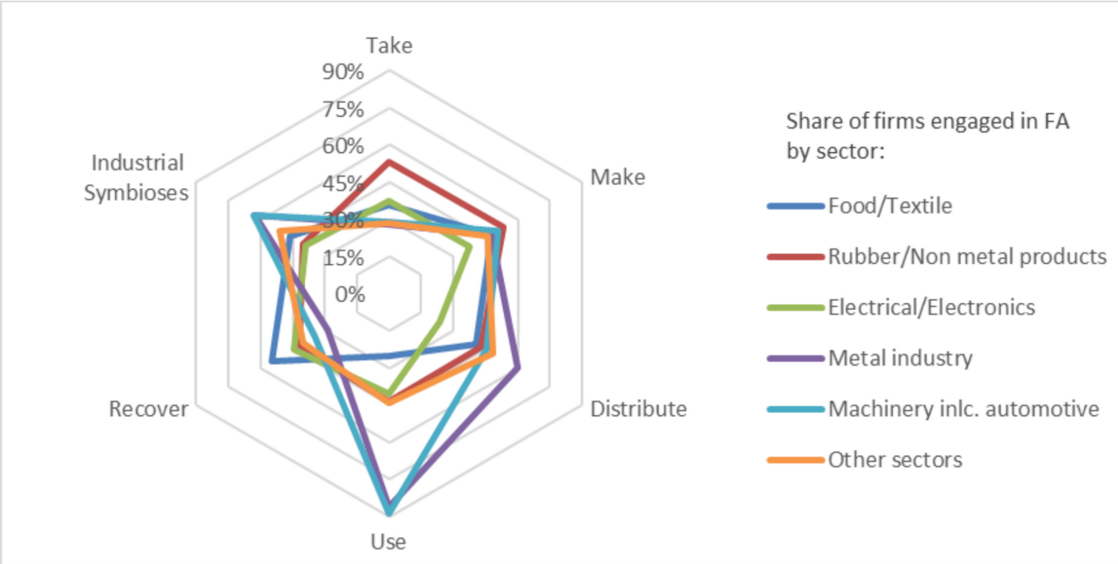

FIGURE 3 | Share of companies engaged in FA, by sector.

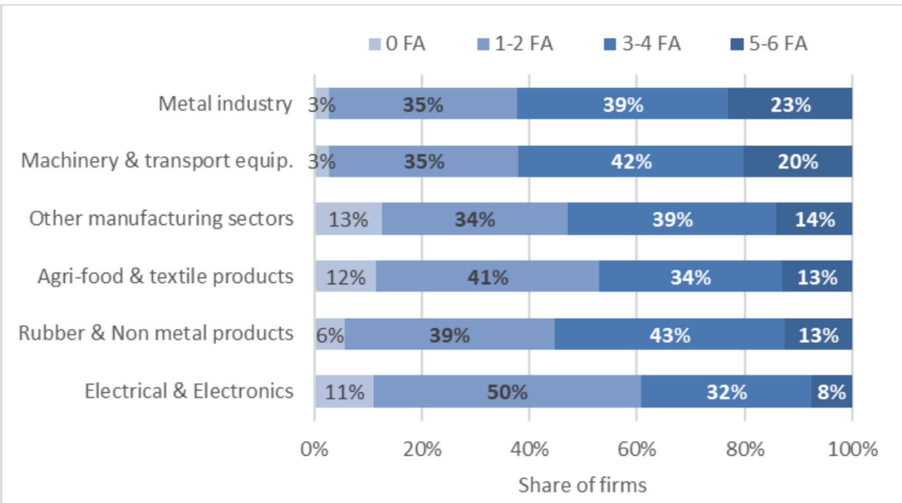

FIGURE 4 | Number of FAs adopted, by sector.

Figure 5 shows that large companies have a high level of adoption of CE practices, whereas a considerable share of small companies has a low level of adoption. Furthermore, 13% of small firms do not engage in any FA, compared to 1% of large firms. RQ3 used the same statistical test as RQ2, obtaining a significance of 0.000, below the established *p*-value (<0.05). Differences are upheld and the level of CE practices adopted differs significantly according to company size.

RQ4: *What correlation is there between EMS implementation and a higher adoption of CE initiatives in manufacturing companies?*

Figure 6 shows the level of adoption of CE initiatives by manufacturers according to EMS application, indicating that EMS use is linked to a higher level of CE adoption.

Thereby, the group comparison reveals statistically significant differences ($p < 0.01$). To illustrate, we can also look at the share of EMS users according to the level of CE adoption. This shows that almost half of the firms that engage in five or six FAs use an EMS. In contrast, only 50% of firms with three or four FAs use an EMS. Both results support the conclusion that the more intensively firms are engaged in CE practices, the more they use an EMS.

The literature points out that large companies use formalised organisational practices such as the EMS much more frequently than small companies for several reasons. Thus, we explored in depth how company size affects the correlation between EMS use and adoption of CE practices. Figure 7 shows the percentage of EMS users in relation to CE adoption for three sizes of company, revealing a particularly strong relationship for larger companies. However, even small and medium sized companies show a higher level of adoption of circular practices in relation to higher EMS use. For all three company size groups, statistical tests show that the differences in the share of EMS users

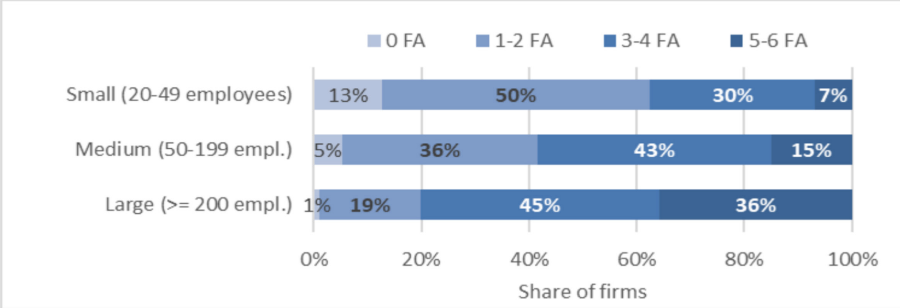

FIGURE 5 | Number of FAs adopted, by company size.

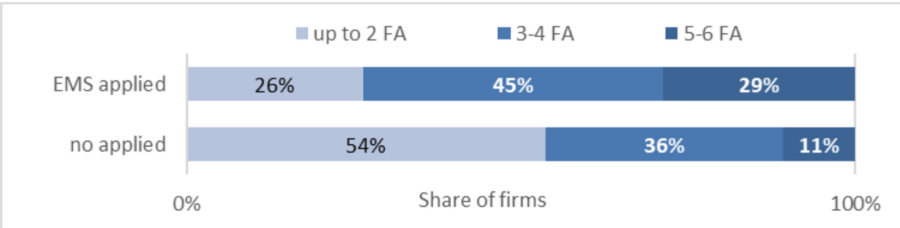

FIGURE 6 | Percentage of companies with an EMS in relation to the number of FAs adopted.

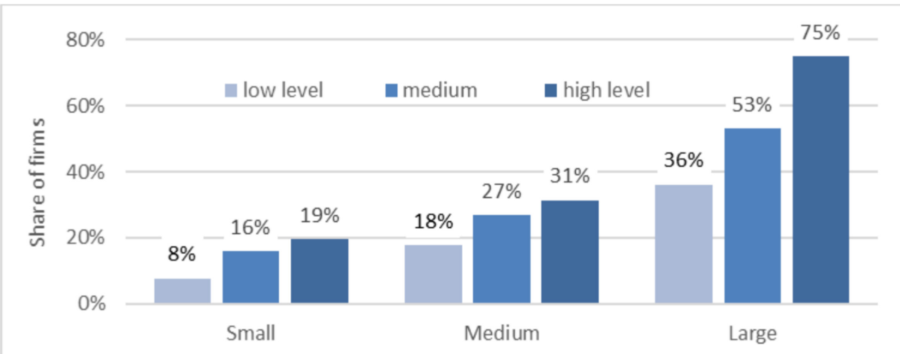

FIGURE 7 | Percentage of companies with an EMS in relation to the number of FAs adopted, by size.

is statistically significantly ($p < 0.05$) depending on the level of adoption of CE initiatives. Thus, the more intensively firms are engaged in CE practices, the higher the percentage of EMS use.

Further analyses also revealed that even when multinomial regression models are used to control sectoral affiliation and firm size simultaneously, EMS use is positively associated with CE adoption level. Companies using EMS are likely to adopt CE initiatives more intensively, therefore company size is the most important factor in this estimation. Furthermore, separate modelling for the different sized groups validate this conclusion. It should be noted that sectorial differences are greater among small firms.

5 | Discussion

This study seeks to expand and complement previous research on the level of adoption of CE practices in manufacturing firms, particularly regarding sector, company size and whether an EMS is in place.

Regarding RQ1, our research adopted two perspectives. First, if we consider only the firms with at least one circular practice in relation to a FA, then Use is the most adopted FA. A large number of manufacturers offer innovative products that reduce the environmental impact of the product and offer services integral to any circular economy. Furthermore, considering the importance of Industrial Symbioses, many manufacturers are interconnected with other companies through cooperation. Far fewer firms can adopt technologies using recycled materials or water in their production processes. The second perspective arises from the intensity with which companies are involved in the FAs. Here, the most significant FAs are Recovery followed by Distribution and Use. The Recovery FA is corroborated by studies by Fonseca et al. (2018) and Prieto-Sandoval, Ormazabal et al. (2018). This implies that firms are already engaging in this FA will be more intensely engaged therein. These results also show that to analyse the level of adoption of CE practices, it is useful to analyse the FA separately. Future studies could analyse Distribution and Use FAs in greater detail to observe whether regional or national regulations or incentives influence the results of these fields.

Regarding RQ2, the sectors most active in adopting CE practices were Machinery & Transport Equipment and the Metal industry, and the FA showing the most marked differences between sectors was Use. To our knowledge, no previous studies focus on FAs applied in specific industrial sectors, although the literature does mention CE practices; for example, products with reduced energy consumption during use or product refurbishing and retrofitting services. This proves that these industrial sectors have taken significant steps in the transformation towards circularity through Eco-design. Nevertheless, that practices mentioned in previous studies show no significant results; for example, extension of useful life or servitisation (L. M. Fonseca et al., 2018; Jaime Ferrer (Coord.) 2021), which may behave differently depending on the sector, and must be adapted and analysed accordingly. However, it can be also concluded that opportunities to offer innovative products with reduced environmental impact, which is an integral part of any circular economy, differ greatly between sectors. This may be linked to the production process and the raw materials used to produce product parts in both sectors. Nonetheless, the activity sector and level of CE adoption in manufacturing firms are correlated.

On reviewing RQ3 statistically and examining whether there was a correlation between company size and a higher adoption of CE initiatives in manufacturing companies, findings indicate significant differences regarding company size. This confirms studies by Bassi and Dias (2019) and Howard et al. (2022) highlighting the difficulties faced by SMEs when adopting CE practices compared to large companies. This is mainly due to weaknesses SMEs face related to staff training, technological support, and access to advice and financing. Findings show a significantly high level of adoption of CE practices in large companies and a low level of adoption of CE practices in a large number of small companies.

Finally, in line with previous literature (Barón Dorado, Giménez Leal, and de Castro Vila 2022; L. M. Fonseca et al., 2018; Jain, Panda, and Choudhary 2020; Zhu, Cordeiro, and Sarkis 2013), findings for RQ4 indicate that manufacturing companies with an EMS in place adopt a higher level of circularity practices, and the higher the level of adoption of CE initiatives, the more likely the firms are to use an EMS.

Furthermore, the study shows a relationship between EMS use and CE adoption for all firm sizes when monitoring for size and sector simultaneously. Thus, we can conclude that having an EMS in place favours companies' adoption of circular practices in a greater number of FA, regardless of size. This indicates that the EMS may facilitate circularity adoption, particularly in small companies facing greater challenges adopting the model due to constraints that large companies overcome more easily.

This research makes a significant contribution to both theoretical understanding and practical implications in the context of CE practices within manufacturing firms. Regarding the theoretical contribution, this research applies the PBV theory to the context of CE practices within an organization and shows that focussing on actual practices and the industrial context helps to understand the adoption behaviour. Regarding to practical contributions, the findings broaden the existing literature by providing a holistic view of adoption patterns across different sectors and company sizes. Identifying key FAs such as Recovery, Distribution and Use, together with in-depth sectoral analysis, enhances our theoretical understanding of the nuances of CE adoption. This study highlights the critical role played by Machinery & Transport Equipment and the Metal industry sectors, shedding light on the specific practices that drive circularity within these industries. Furthermore, the correlation between company size and adopting CE initiatives reaffirms the existing challenges faced by SMEs. The positive relationship between implementing EMS and the intensity of circularity practices also contributes to the literature, emphasising the role of EMS as an enabler to overcome adoption barriers. This holistic review not only enriches academic debates on the adoption of CE, but also provides practical insights for policy makers and industry practitioners seeking to promote sustainable practices within manufacturing.

6 | Conclusions

The design, manufacture, use, and end-of-life management of products have a significant impact on their demand for natural resources, contribution to climate change, and the volume of waste generated. Therefore, regulators, businesses, and consumers all have a key role to play in advancing circular solutions to address these critical concerns. In light of this, the aim of this article was to analyse CE adoption practices related to FAs in manufacturing firms and investigate potential variations in adoption according to sector, company size, and EMS implementation.

Findings reveal the importance of Recovery, Distribution and Use FAs, with variations observed across sectors. The Machinery & Transport Equipment and the Metal industry sectors particularly emphasise Use practices. It is also evident that while larger companies are leading the way in adopting CE practices, SMEs still face challenges. The positive correlation between EMS implementation and CE adoption underscores the influential role played by EMS in promoting CE principles, particularly within SMEs. These results emphasize the need to tailor CE strategies to specific industry sectors and company sizes and highlight the significance of EMS as facilitators for the adoption of CE practices. Future research should focus on a more in-depth analysis of the Distribution and Use and its relationship with regional and national regulations and policies, as well as a comprehensive investigation of the barriers and opportunities faced by SMEs in the transition to CE. Further research should aim to consolidate these findings by broadening the sample to include other countries and other data sources.

While this study provides valuable insights for current research, it has limitations. Firstly, the study is limited to one country-specific context and focuses exclusively on the manufacturing industry in Germany. Future studies should broaden their scope to different contexts and countries to provide valuable insights into different mechanisms for adopting CE practices and the facilitating role EMS implementation plays. Secondly, a more practice-based approach would deepen knowledge of FAs and enable a more precise understanding of the barriers to implementation. Similarly, in-depth analysis of the different FAs could also provide useful information. Finally, this study primarily focuses on differences in adopting CE practices in relation to the basic characteristics of firms. Future research could explore other production and market mechanism characteristics in more detail, as well as other potentially moderating factors e.g. degree of digitalization, providing a more nuanced understanding of the adoption processes. The debate on Industry 5.0 and a human-centred approach to digitalisation particularly emphasises the synergy between operational development and new technologies with a view to fostering innovative capacity, highlighting the importance of ecological innovations from both a process and product perspective.

Author Contributions

The manuscript was written by G.G.L., R.d.C.V., A.B.D. and A.J. All the authors contributed to the conceptualization, methodology, formal analysis, writing–original draft preparation and writing–review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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