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Antecedents of circular manufacturing and its effect on environmental and financial performance: A practice-based view

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ABSTRACT

Despite the worldwide recognition of the Circular Economy (CE) philosophy, its comprehensive adoption in manufacturing is not well understood in literature and practice. This study theorizes circular manufacturing (CM) by extending the cleaner production concept according to the design thinking of CE. Drawing on the practice-based view, it develops a conceptual model on the antecedents and performance outcomes of CM and the moderating role of Industry 4.0 (I4.0) production technologies on CM-to-environmental and financial performance relationships. The research adopts a mixed-methods approach to examine the hypothesized relationships. Survey data from 255 Chinese manufacturers are analyzed using structural equation modeling and hierarchical regression. Two qualitative case studies verify the survey findings and offer additional insights. The findings suggest that by strengthening a CE culture and integrated management systems, firms can improve CM implementation and consequently environmental and financial performance. However, investing in I4.0 production technologies may not enhance the impact. Our research contributes to the literature by conceptualizing and operationalizing CM as a new construct. It also provides guidelines for implementing CE in manufacturing.

1. Introduction

Manufacturers nowadays face immense pressures to operate in an environmentally friendly and socially responsible manner (Farooque et al., 2022; Treacy et al., 2019). There is a growing consensus that the currently dominant "take-make-dispose" linear economic model is unsustainable, and the world should accelerate the transition to a circular economy (CE) (Ellen MacArthur Foundation [EMF] 2022). The CE concept enables firms to rationalize their resource consumption while balancing their environmental, economic, and social performance outcomes (Ghisellini et al., 2016; Rodríguez-Espíndola et al., 2022). It is based on three principles, all driven by design, which are to (i) eliminate waste and pollution, (ii) circulate products and materials (at their highest value), and (iii) regenerate nature (EMF, 2022). To implement CE, manufacturers need to embrace the design thinking of CE, which is embedded in these CE principles, into their manufacturing systems (Acerbi and Taisch, 2020; Ghisellini et al., 2016). However, adoption of CE principles in manufacturing systems has remained an under investigated research area.

Recently, Antonioli et al. (2022) and Garza-Reyes et al. (2019) called for research in circular manufacturing (CM), the integration of CE principles in manufacturing systems. Specifically, they highlight a knowledge gap in the operationalization of CE principles and practices in the context of manufacturing systems. Although the term 'circular manufacturing' has been increasingly used in both practice and research, it remains unclear what constitutes CM and how to operationalize CM in practice and quantitative empirical research. The extant literature reports important antecedents to sustainability practices, for example, an organization's sustainability culture (Pagell and Wu, 2009) and prior experience of implementing integrated management systems (IMS) (Dey et al., 2020; González-Benito and González-Benito, 2005). Similarly, we can posit that CE culture and IMS drive CM adoption. However, the theoretical proposition has not been empirically tested.

On the other hand, there is an abundance of research suggesting sustainability practices are positively related to firm performance

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(Govindan et al., 2020). However, there are also studies suggesting that CE implementation may be economically challenging (Genovese et al., 2017; Nasir et al., 2017). Therefore, it is essential to examine the impact of CM on firm performance. Furthermore, in recent years, Industry 4.0 (I4.0) technologies have been seen to improve operational and sustainability performance (Rosa et al., 2020; Zheng et al., 2021). The EMF (2022) also recognizes technologies as a key enabler of circularity to eliminate waste and pollution. Note that I4.0 encompasses a diverse range of digital technologies and those specifically used in production/manufacturing do not necessarily have the same casual properties as others. However, to date, the role of I4.0 production technologies, a subset of I4.0 technologies, in CM adoption remains largely unexplored. Given these knowledge gaps, this research sets the following objectives.

- To theorize what constitutes CM and how to operationalize it
- To empirically verify the antecedent roles of CE culture and IMS in CM adoption
- To empirically investigate the effect of CM adoption on firm environmental and financial performance
- To understand the moderating role of I4.0 production technologies in the CM-to-firm environmental and financial performance.

To achieve these research objectives, we employ a sequential mixed-methods approach through the theoretical lens of the practice-based view (PBV) (Bromiley and Rau, 2014, 2016). The quantitative phase obtained survey data from 255 Chinese manufacturers across different industrial sectors. The qualitative phase studied two real-life cases of representative Chinese manufacturers.

This study makes several original contributions. *First*, unlike earlier studies that rely on theories from other academic disciplines, we apply the PBV, a theory rooted in the operations management discipline, in the CE context. *Second*, drawing upon PBV and a review of extant literature, we establish CM as a strategy that integrates the design thinking of CE in manufacturing systems. This pioneering work also operationalizes the measures of CM. *Third*, we confirm the antecedent role of CE culture and IMS in CM adoption through rigorous survey data analysis and case studies. *Fourth*, we establish the positive impact of CM adoption on firm environmental and financial performance. *Last*, we find out that I4.0 production technologies do not moderate the relationship between CM and environmental and financial performance although it has a direct and positive impact on financial performance.

The paper is organized as follows. Section 2 reviews the relevant literature. Theoretical background and hypothesis development are presented in section 3. We present our mixed-methods research approach in section 4. Survey and case study results are presented in section 5 and 6 respectively. Section 7 discusses the results and findings besides highlighting the theoretical contributions and practical implications. Section 8 concludes the study.

2. Literature review

2.1. The CM concept

Cleaner production (CP) (Ghisellini et al., 2016), sustainable manufacturing/production (Golicic and Smith, 2013; Linton et al., 2007) and green manufacturing (M. Lo, 2014) are the main concepts related to achieving sustainability in manufacturing. All these concepts had been in practice before CE became widely known. Particularly, CP has been widely promoted for over two decades and has received much research attention (Farooque et al., 2022). The United Nation Environment Programme [UNEP] defines CP as “the continuous application of an integrated preventative environmental strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment” (p.3). CP focuses on material/energy conservation and efficiency, elimination of toxic raw materials and toxic emissions, and reduction of overall environmental impacts in the production processes (Ghisellini et al., 2016). In operationalizing CE in a firm’s manufacturing systems, CP is often viewed as a preparatory strategy (Ghisellini et al., 2016).

For manufacturers to adopt CE principles in their manufacturing systems, it is essential to design products intentionally for circularity of materials without creating wastages in the entire product lifecycle (den Hollander et al., 2017). This confers importance to the emerging concept of circular product design (CPD) (Bocken et al., 2016; Burke et al., 2021). CPD applies CE design principles to enable product design function to think beyond its functional focus to consider supply chain processes to realize the circulation of resources embedded in products. For example, products should be designed for convenient disassembly to facilitate efficient value recovery at the end of their useful life (Farooque et al., 2019).

The concept of CPD advances the older design approaches such as eco-design and design for sustainability (DfS) (Wang et al., 2022). Eco-design considers the environmental aspects of product design while aiming to reduce the negative environmental impacts throughout the lifecycle (Brezet, 1997). DfS moves beyond the environmental aspects to consider social, economic, and ethical dimensions of product design (Spangenberg et al., 2010). However, CPD significantly differs from these design approaches by emphasizing resource circularity and end-of-life options (Burke et al., 2021; Farooque et al., 2019). CPD follows a cradle-to-cradle approach as opposed the cradle-to-grave approach of the traditional design concepts. The cradle-to-cradle approach embraces circular thinking to achieve an indefinite circulation of resources.

The main aim of the CPD strategy is to slow and close resource loops (Bocken et al., 2016). The resource loops can be slowed by design strategies focusing on durability and product life cycle extension (Burke et al., 2021). In terms of closing resource loops, CPD implies designing a *restorative* cycle for technical materials and a *regenerative* cycle for biological materials (Zhang et al., 2021), supported by simplified disassembly and reassembly requirements (Burke et al., 2021; Farooque et al., 2022). In a nutshell, a CM strategy should build on CP but, at the same time, CPD plays a crucial role in implementing CM to achieve CE goals (Asif et al., 2021). Therefore, it seems logical to posit that CM should integrate CPD and CP in operationalizing CE principles in a firm’s manufacturing system.

Our conceptualization of CM is consistent with the working definition of CM provided by Acerbi and Taisch (2020) who performed a systematic literature review of 215 research articles to develop a theoretical framework of CE strategies in manufacturing sector. They specifically advocated the concurrent adoption of strategies such as CPD and CP, among others, to “reduce resources consumption, to extend resources lifecycles and to close the resources loops” (Acerbi and Taisch, 2020, p. 12).

2.2. Research on CM

The importance of CM has been increasingly emphasized in the recent literature, however, the scholarly knowledge on CM is still in infancy stage. Only a handful of research studies have demonstrated an explicit focus on the interaction of CE principles with the manufacturing operations at the firm level. Table 1 provides a summary of the most relevant literature on CM.

Three research themes are observed in the publications summarized in Table 1. The first theme is related to CM implementation. In this theme, Prosman and Cagliano (2022) deal with how to configure CM systems in the context of circular business models. Chari et al. (2022) study the implementation of CM supply chains from a dynamic capabilities perspective. Roci et al. (2022) suggest that CM system implementation requires a lifecycle approach for measuring performance in cost, revenue, and environmental impacts. The second theme addresses the relationship between lean management and CM. For example,

Table 1
Summary of the CM literature.

Reference	Research topic	Methodology	Research context	Key findings
Prosman and Cagliano (2022)	CM configurations for the circular business models	Empirical Qualitative Comparative Analysis	Europe, Northern America and Australia Manufacturing Start-ups (Multiple Industries)	Three successful CM configurations were identified which provide insight into the main elements of manufacturing configurations in circular business models. CM configurations are further aligned with typical supply characteristics in a CE to provide insights into when (not) to apply a given manufacturing configuration.
Afum et al. (2022)	Interaction between lean management and circular production systems and their implications on zero-waste performance, green value competitiveness and social reputation.	Empirical Survey	Ghana Manufacturing Small and Medium Enterprises (Multiple Industries)	The study results suggest that lean management plays a vital role in the implementation of circular production systems. Lean management and circular production systems, when combined, have a significant effect on zero-waste performance, green value competitiveness and social reputation. Further, the mediation role of circular production system between lean management, zero-waste performance, green value competitiveness and social reputation is also confirmed from the study results.
Schmitt et al. (2021)	Achieving circularity in a lean manufacturing context	Empirical Case study	Sweden Manufacturing (Heavy-duty and off-road Industry)	The study results suggest that lean and linear production do not see waste as a resource. Adoption of circular perspective in a lean manufacturing context has the potential to bring about environmental and economic gains at the system, process, and product levels.
Kannan et al. (2022)	Green Manufacturing in paving forward the green transition in manufacturing operations	Literature Review	N/A	This research proposes a conceptual framework to support the adoption and implementation of green manufacturing through mitigating adoption challenges by considering critical success factors. Full implementation of green manufacturing is expected to assist the transition towards the next phases of sustainable strategies in manufacturing such as sustainable manufacturing and CM.
Chari et al. (2022)	Dynamic capabilities for CM supply chains and the role of supply chain resilience and industry 4.0	Empirical Qualitative Case study	Europe Process Industry	This research describes challenges to implement CE and identified dynamic capabilities which enable circular and resilient manufacturing supply chains. It further develops a dynamic capabilities model for CE implementation, maps causal relationship between the capabilities and formulates research propositions for CE implementation.
Govindan (2022)	Barriers to integrating Blockchain Technology in remanufacturing for achieving CM	Empirical Multi criteria decision making technique	Denmark Remanufacturing (Automotive Parts)	The study identified scaling of technology, operational challenges, and lack of awareness on blockchain risk as key barriers to blockchain technology implementation in remanufacturing for achieving CM.
Delpla et al. (2022)	IoT enabled CM for closed loop supply chains	Modeling Optimization	Denmark Manufacturing (Mobile Phones)	The study results suggest that the full implementation of a tracking technology on all recoverable end-of-life (EoL) products enabled by an IoT intelligent device called Device Internet of Things (DIOT) would be beneficial by more than 5.3% for high remanufacturing costs. The profit would increase by more than 49% if the quantity of recoverable EoL products exceeded the demand for refurbished products.
Roci et al. (2022)	Implementation of CM systems	Modeling and Simulation + Case Study	Europe Manufacturing (White Goods)	The study results reveal that CM system necessitates a lifecycle approach in terms of costs, revenues, and environmental impacts. Furthermore, decision related to business models, product design, and supply chain affect the CM performance.
Acerbi and Taisch (2020)	Adoption of CE principles in the manufacturing sector leading towards creation of CM strategies	Literature Review	N/A Manufacturing	The study provides a definition of CM besides identifying and analyzing various CM strategies. The two major streams of CM research include: technologies and assessment methods and models. The authors also suggest future research directions.
Sun et al. (2020)	Pricing strategy for 3D printing or additive manufacturing for CM in a closed-loop circular supply chain	Modeling Optimization	N/A	The study findings suggest that quality of the recycled material has a significant impact on the 3D printing platform's and material suppliers' (i.e., conventional, and recycled material suppliers) decision-making. A 3D printing platform that sells both the virgin material product and recycled material product (RMP) prefers printing high-quality RMP as its profit increases. However, both the material suppliers avoid printing high-quality RMP as the optimal prices of the material suppliers decrease with the quality of the RMP.

Schmitt et al. (2021) and Afum et al. (2022) suggest that lean manufacturing plays an important role in the implementation of CM. Furthermore, lean management and CM, when combined, have the potential to bring about enhanced performance outcomes across the three dimensions of the triple bottom line (TBL). The role of I4.0 technologies in the implementation of CM appears to be the most popular research theme. I4.0 technologies are seen a key enabler of the CM supply chains (Chari et al., 2022). Specifically, IoT (Acerbi and Taisch, 2020; Delpla et al., 2022), blockchain technology (Govindan, 2022) and 3D printing (Sun et al., 2020) have been identified as the supportive technologies facilitating the implementation of CM.

Except for Afum et al. (2022), all the empirical studies in Table 1 are based on a developed country context. It is a surprise that no study has been conducted in China on the emerging CM topic although the country has enforced CP and CE related legislations in its manufacturing sectors for about two decades (Geng et al., 2009). Furthermore, Chari et al. (2022) and Prosman and Cagliano (2022) believe that a firm's culture that is supportive of CE plays an important role to enable the circular transition. Firms having a CE culture upskill their employees to bring about changes in the manufacturing process required for CM implementation (Chari et al., 2022; Govindan, 2022). However, no study has focused on CE culture or provided empirical evidence of its antecedent role in CM implementation.

In summary, research on CM is nascent. A few studies suggest that I4.0 technologies enable the implementation of CM but further and more rigorous empirical validation are required. Research on the antecedent role of company culture and lean management system for CM implementation has just started to emerge. There are ample rooms to expand the research scope to cover the role of CE culture and other management systems such as International Organization for Standardization (ISO) quality management systems and total quality management (TQM) system. Moreover, the performance implications of CM remain underrepresented and largely unexplored. Although CM has the potential to enhance firms' sustainability performance, there is dearth of empirical evidence to support such claims, especially in the context of China. This study narrows these research gaps in the CM literature.

3. Theoretical background and hypothesis development

3.1. Practice-based view

The PBV seeks to explain the improvement in firm performance due to the adoption of a range of practices – *i.e.*, activity or a set of activities – that a variety of firms can execute which are imitable, publicly available, and amenable to transfer across firms (Bromiley and Rau, 2014; Carter et al., 2017). This research adopts the PBV as a theoretical lens for two main reasons. *First*, sustainability concepts and practices, including those related to CE, have been extensively studied in the literature and are widely available to the public. For example, circular supply chain management (Batista et al., 2018; Farooque et al., 2019; Zhang et al., 2021) and circular product design (Burke et al., 2021) have been proven valuable. *Second*, China, the research context, has implemented a stringent CE policy framework for about two decades. Consequently, Chinese manufacturers have adopted a variety of CE practices due to regulatory pressure. Therefore, the concerned CM practices in this study conform to the criteria set by the PBV – namely, imitability, availability in the public domain, and transferability across firms. Moreover, we intend to measure firm performance as the dependent variable which is also in line with the PBV.

We believe the PBV is more suitable for this study than the popular resource-based view (RBV) (Barney, 1991). Bromiley and Rau (2016) argued that the RBV is not aligned with the activities and objectives of operations management studies in several ways. In the RBV, the dependent variable is sustained competitive advantage, thus only a small number of long-term industry-leading firms are suitable to be investigated through the RBV (Treacy et al., 2019). Competitive advantage exists at the business or the firm level, and this does not directly translate into the operations level. Measuring sustained competitive advantage is also difficult. The RBV deals with resources that are valuable, rare, and difficult to imitate. Such resources are also difficult to measure due to their uniqueness. Based on these issues, Bromiley and Rau (2016) suggested that the PBV would make a better theoretical lens for operation management studies. The core proposition of the PBV is that firms' performance variations can be explained by the heterogeneity in their implementation of operational practices. Such heterogeneity is often inevitable across firms because of bounded rationality and varying constraints in capacity and time for implementing operational practices.

3.2. CE culture and CM

The transition towards CE is a paradigm shift which requires a continuous state of adjustment; reviewing actions and operations; redesigning procedures and structures; and reinventing mindsets (Kjaer et al., 2019). Individual concerns about and organizational values relating to CE can guide firms toward shared values and beliefs that prioritize sustainability and circularity in their business models (Bansal, 2003; Henry et al., 2020), balancing economic efficiency, environmental responsibility, and social equity in their decision-making (Marshall et al., 2015; Pagell and Wu, 2009). Thus, CE culture is expected to play a significant role in driving a fundamental reorientation of business towards CE.

The extant literature is relatively silent on the antecedent role of CE culture in a firm's CM adoption. However, previous studies suggest that a sustainability culture supports the implementation of sustainability practices in production processes (Chari et al., 2022; Marshall et al., 2015; Pagell and Wu, 2009). This is because a sustainability culture provides an atmosphere where firms consider all three dimensions of sustainability in every decision they make (Marshall et al., 2015), not only in manufacturing but also in developing sustainable new products (Pagell and Wu, 2009). On the contrary, an absence of a sustainability culture creates barriers to an organization's commitment to CE (Prosman and Cagliano, 2022; Wang et al., 2022). Thus, we hypothesize.

H_1. CE culture has a positive impact on CM implementation

3.3. IMS and CM

According to Porter's (1996) seminal work on strategy, firms are always on the quest for productivity, quality, and speed. As a result, a remarkable number of management systems have been developed and implemented by firms. They include TQM, Lean/just-in-time (JIT), and ISO systems for quality management (e.g., ISO 9001) and environmental management (e.g., ISO 14001) (Villena et al., 2021). They are collectively referred to as IMS in this study.

No study has investigated the role of IMS in CM adoption. However, IMS seem to support CE's aspiration to maximize resource efficiency. Specifically, *TQM* continuously improves product and process quality to meet or exceed customer expectations (Cua et al., 2001). *Lean/JIT* reduces or eliminates non-value-adding activities to improve speed, cost efficiency and customer value, thereby contributing to sustainability performance (Piercy and Rich, 2015; Yu et al., 2020). In particular, lean management and CM are seen to have common goals such as waste elimination (Afum et al., 2022). Since lean manufacturing systems have remained dominant in the linear paradigm, CM systems will have to build on the existing lean manufacturing systems (Schmitt et al., 2021). As the world's most widely adopted management system standards (Marimon Viadiu et al., 2006), *ISO 9000* and *14,000* series strengthen environmental management systems, although the effect of the latter is more direct (Bernardo et al., 2012; González-Benito and González-Benito, 2005; Zhu and Sarkis, 2004). Given that IMS support the achieving of CE goals, we hypothesize the following.

H_2. IMS have a positive impact on CM implementation

3.4. CM and firm performance

The effect of CM on firm performance is likely to be on all dimensions of the TBL due to the nature of the CE concept (Ghisellini et al., 2016). This research, however, only deals with long-term financial and environmental performance. It does not consider the social dimension in order to allow for a more focused and in-depth investigation.

A meta-analysis of the literature by Govindan et al. (2020) provides strong evidence that, generally speaking, sustainability practices have a positive impact on financial performance. CE adoption often requires major initial investments in new equipment and modifications in the processes (Geng et al., 2009), so it may be economically challenging as suggested by the case studies of Genovese et al. (2017) and Nasir et al. (2017). Whereas the survey studies by Zhu et al. (2010, 2011) suggest that CE practices have a positive association with economic performance among Chinese manufacturers. In China, the government has mandated firms to implement CE in the last two decades. So, it is reasonable to assume that most firms are experiencing the long-term financial impact of CM. Given our focus on long-term financial performance, we hypothesize.

H_3. CM implementation has a positive impact on financial performance

The positive impact of sustainable manufacturing practices on environmental performance is well-established in the literature (Golicic and Smith, 2013; Linton et al., 2007). CM has the potential to further enhance the environmental impact along the product lifecycle. *First*, by virtue of CPD, it facilitates slowing and closing material loops by means of a systemic supply chain-wide circulation of resources (Burke et al., 2021). *Second*, by virtue of CP, it improves material/energy conservation and efficiency, preventing the use of non-renewable, toxic raw materials and toxic emissions (UNEP, 2006) Integrating CPD and CP, CM enables firms to control, monitor and prevent pollution, wastages, and emissions, resulting in less environmental damage. Therefore, we hypothesize the following.

H_4. CM implementation has a positive impact on environmental performance

3.5. Moderating role of I4.0 production technologies

The I4.0 concept is also known as smart manufacturing, characterized by interconnected machines and intelligent products and systems (Tortorella and Fettermann, 2018). I4.0 technologies include the Internet of Things (IoT), Big Data analytics, cloud computing, blockchain, and artificial intelligence, among others (Yadav et al., 2020; Zheng et al., 2021). Using these technologies, firms can achieve integration of manufacturing processes (both vertical and horizontal) and product connectivity which can lead to better product and operational performance (Dalenogare et al., 2018). For example, Intel, one of the world's largest semiconductor manufacturers, revamped its production process using big data analytics capability while reporting significant performance improvements (Mikalef et al., 2019). It is also believed that I4.0 technologies can enable firms to achieve higher levels of sustainability performance (Luthra et al., 2020; Yadav et al., 2020; Zheng et al., 2021).

I4.0 technologies are found to be a main enabler in the context of CE implementation (Rosa et al., 2020). These technologies can facilitate the circularity of resources within supply chains (Lopes de Sousa Jabbour et al., 2018). In the context of CM, digital technologies such as IoT, blockchain, and 3D printing facilitate the implementation of a smart CM system (Acerbi and Taisch, 2020; Delpla et al., 2022; Roci et al., 2022; Sun et al., 2020). Given the enabling role of I4.0 technologies in a CE transition, we hypothesize that I4.0 production technologies can enhance CM's financial and environmental performance outcomes. Hence, we posit the following hypotheses.

H_{5a}. I4.0 production technologies positively moderate the relationship between CM and financial performance.

H_{5b}. I4.0 production technologies positively moderate the relationship between CM and environmental performance.

Fig. 1 summarizes the hypothesized relationships between the study constructs. Firm size, ownership type and industry are the three control variables.

4. Research methodology

This research adopts a sequential mixed-methods approach (Li et al., 2020), including a survey of 255 Chinese manufacturers and two explanatory case studies. The survey involved a wide range of manufacturers to ensure the generalizability of findings, while the case studies further validated the survey results, provided more in-depth understanding to interpret the survey findings, and offered additional insights. We explain our survey research design in section 4.1 followed by case study research design in section 4.2.

4.1. Survey design

4.1.1. Questionnaire development

We reviewed the related literature extensively to develop construct measures. Appendix A provides the sources from which the measures were adapted. In this research, we modeled CM as a second-order construct with CPD and CP being the first-order constructs – as discussed in Section 2.1. We adopted construct measures from the English literature and developed a questionnaire in Chinese. Two researchers who are fluent in both English and Chinese followed a back-translation technique to ensure that the measures in the Chinese questionnaire were conceptually equivalent to the original ones developed in English (Paulraj et al., 2017). We ran two rounds of pilot tests in face-to-face meetings. Each round involved seven senior managers from large-scale manufacturers in China. They provided feedback on questionnaire design related to the wording of measures and suggestions for adding/removing certain measures. We incorporated their suggestions in the final questionnaire. This process improved the questionnaire by ensuring content validity and lowering the chance of misinterpretation by survey respondents.

The questionnaire included two parts. Part I covered control variables and dependent variables (i.e., firm performance). The respondents rated firm performance in comparison with their firm's main competitor in the industry. The measures were rated on a seven-point Likert-type scale (1 = significantly lower; 7 = significantly higher) which is considered better for managing social desirability bias (Stöber et al., 2002). Part II included questions on CE culture, IMS, CM, and I4.0 production technologies. The respondents evaluated the situation in their respective organizations in the last year. We used a five-point Likert scale anchored at 'strongly disagree and strongly agree' for CE culture; 'not at all and to full extent' for IMS, CM and I4.0 production technologies. We intentionally asked the respondents to rate firm performance in the current year while CM implementation in the last year. Incorporating a time-lag between CM implementation and its performance effects served to reduce possible bias (Dobrzykowski et al., 2016).

4.1.2. Survey administration

Survey data for this research were collected in 2019. We distributed questionnaires through multiple channels including professional associations, postgraduate and MBA/EMBA students and local government officials. A total of 930 survey questionnaires were distributed to manufacturers across all the six greater administrative areas of China. In

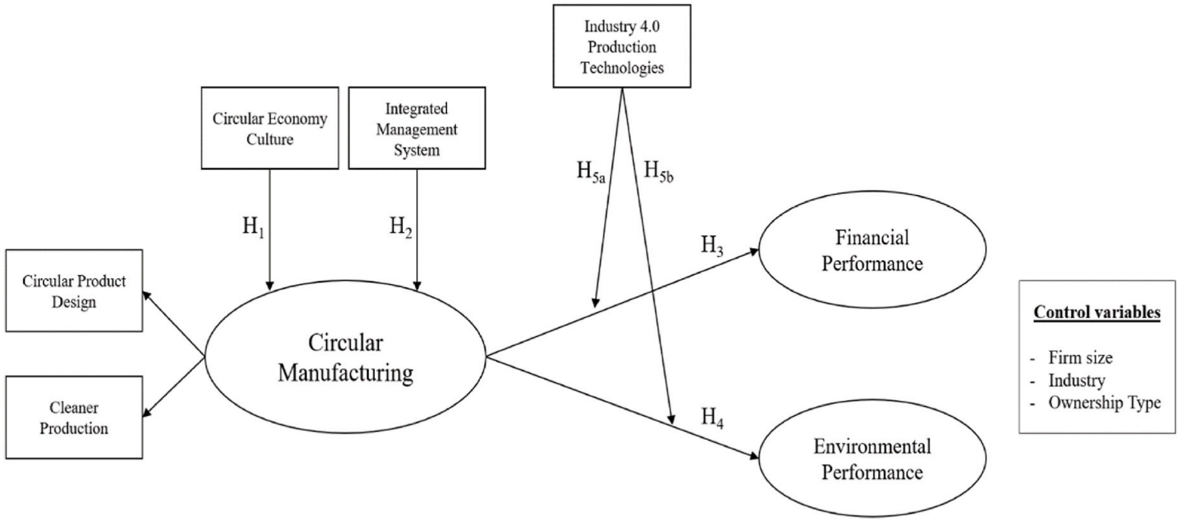

Fig. 1. The conceptual model.

total, 360 completed questionnaires were returned, *i.e.*, a response rate of 38.71%. The lead researcher scrutinized all the responses to ensure data quality. A large proportion of responses (n = 105) were rejected based on missing data, inattentiveness to scale variations and similarity in response patterns. The final included 255 responses and the sample demographics are provided in Table 2.

We attempted a split survey method (Dubey et al., 2015; Podsakoff et al., 2003) to ask different respondents within the same organization to complete questions related to indepdent variables (in Part II) and dependent variables (in Part I), respectively. Part I requested a response from a senior manager who was knowledgeable in firm performance. Part II requested a response from a senior manager who was familiar with the operations. Due to the difficulties in managing matched responses, we allowed a single respondent to complete a full questionnaire in the event that it was not possible to recruit two qualified respondents from a firm. In the final sample of 255 responses, 75 were matched responses and 180 were completed by a single respondent.

4.2. Case study design

A case study research strategy is most useful when there is a need to observe how a phenomenon emerges in a specific context (Yin, 2009). We adopted a case study approach to understand how CM works in specific business settings and identify technical, organizational, and other contextual aspects relevant to its implementation. We also investigated how these contextual aspects differ depending on several internal and external conditions. Thus, the aim of the case studies was to complement the quantitative analysis and to provide more in-depth insights on the survey results. Furthermore, the case studies were used as a basis to uncover other aspects that can potentially enable or inhibit performance gains that were not included in the quantitative study (Mikalef et al., 2019).

4.2.1. Case selection

Referring to the national and provincial lists of green factories in China, we selected two case companies: Archroma (Tianjin) Ltd. And Rockcheck United Iron & Steel Group Ltd. Both companies are committed to CM. They represent different industry sectors (chemical vs iron & steel), firm sizes (medium vs large), and ownership types (Chinese-foreign joint venture vs private). We believe they are good representatives of Chinese manufacturers in our study focus.

4.2.2. Case data collection

Case data were mainly collected by face-to-face semi-structured interviews. In addition, secondary data from project reports, newsletters and company websites were collected for triangulation to ensure the reliability and validity of our analysis. The purpose of the interviews was to examine the real-world scenarios of CM implementation. The interviewees were invited to elaborate on their firms' specific CM practices, their impacts on performance, and other influential factors. The main interview questions were are follows.

- Are there any circular manufacturing practices implemented in your firm? How have these practices been implemented? What are the impacts of these practices on enterprise environmental and financial performance?
- What is the state of CE culture and integrated management systems in your firm? How do they influence the implementation of circular manufacturing?
- What are the impacts of the industry 4.0 production technologies on environmental and financial performance?

Case data collection took place between September 2021 and May 2022. In total 15 interviews were conducted with an average length of 45 minutes. Table 3 presents the profile of case study interviewees. All interviews were carried out in Mandarin. Two researchers analyzed the transcribed interview data and met frequently to resolve discrepancies in data analysis. A complete case study draft was checked and approved by both case firms to ensure that there were no misinterpretations.

5. Survey results

5.1. Non-response bias and common method bias

Non-response bias was assessed by comparing early and late waves of returned questionnaires. We conducted two-tailed t-statistics and did not identify statistically significant differences in any of the variables used in the study. Therefore, non-response bias is unlikely to be a concern in our survey data.

We employed several strategies to reduce the possibility and impact of common method bias (CMB) according to the recommendations of Podsakoff et al. (2003); Podsakoff et al. (2012). *First*, the survey was anonymous, and the respondents filled in the questionnaire privately by themselves. We assured the respondents that their answers would be unidentifiable by individuals or organizations. *Second*, we made efforts to collect data from two participants per organization as much as possible using a split survey method, as explained above. *Third*, a number of variations at the construct level besides measurement items

Table 2
Sample demographics for the survey.

Variable	Description	Frequency	Percentage
Firm Size	No. of employees in 2018		
1	<100	50	19.6%
2	101–500	82	32.2%
3	501–1000	39	15.3%
4	1001–3000	37	14.5%
5	3001–8000	22	8.6%
6	>8001	25	9.8%
Ownership	Ownership Type		
1	Private	126	49.4%
2	State-owned	66	25.9%
3	Joint venture	36	14.1%
4	Foreign owned	21	8.2%
5	Collective	5	2.0%
6	Others	1	0.4%
Sectors	Industry		
1	Metals/Metal product/ Machinery/Equipment	73	28.6%
2	Metallurgy	23	9.0%
3	Chemicals	20	7.8%
4	Automotive/Transport equipment/Vehicle	19	7.5%
5	Electrical appliances/Household appliances	19	7.5%
6	Pharmaceutical/Treatment	15	5.9%
7	Food/Beverage/Wine/Tobacco	13	5.1%
8	Building material/Building & decorative	11	4.3%
9	Coke/Petroleum	10	3.9%
10	Electronics/Communication	9	3.5%
11	Textile/Apparel/Leather	6	2.4%
12	Rubber/Plastics	6	2.4%
13	Others	31	9.0%
Supply Chain Position	Role of the firm in supply chain		
1	Raw-material supplier	34	13.3%
2	Component supplier	37	14.5%
3	Original equipment manufacturer	159	62.4%
4	Contract manufacturer	25	9.8%
Annual Sales	Sales revenue in RMB		
1	<1 million RMB	2	0.8%
2	1–4.9 million RMB	7	2.7%
3	5–9.9 million RMB	11	4.3%
4	10–49.9 million RMB	38	14.9%
5	50–99.9 million RMB	15	5.9%
6	100–499.9 million RMB	64	25.1%
7	500–999.9 million RMB	31	12.2%
8	1–4.9 billion RMB	40	15.7%
9	5–9.9 billion RMB	18	7.1%
10	>10 billion RMB	29	11.4%
Respondent Designation	Management level		
1	Top Management (i.e., CEO, COO etc.)	44	17.3%
2	Middle Management (i.e., Director, Dept Head etc.)	161	63.1%
3	Lower Management (i.e., Supervisor, Accountant etc.)	50	19.6%
	Total	255	100.0%

helped us mitigate the CMB as well as social desirability concerns. At the construct level, we followed Pullman et al.'s (2009) example to use firm as a proxy subject for CE practices (Nederhof, 1985).

As mentioned earlier, we attempted a matched response survey. However, most responses (approx. 70%) were received from a single source. Thus, CMB may still be a concern (Guide Jr. and Ketokivi, 2015). In this regard, we performed various tests to detect CMB. Harman's (1976) single-factor test showed the presence of seven distinct factors, whereas the first factor only accounted for 24.12% of the variance. Further, a common latent factor test (Podsakoff et al., 2003, 2012) was performed by introducing a latent variable to the original measurement model. The results indicated that model fit indices of the original model (*i.e.*, $\chi2/df = 1.61$, CFI = 0.95, and RMESA = 0.05) and the common latent factor model (*i.e.*, $\chi2/df = 1.53$, CFI = 0.96, and RMESA = 0.05) were quite similar. Lastly, we performed Widaman (1985) test using two latent variable models. The first being a trait-only model and second included a method factor as well as the traits. The CFI change cutoff criterion of 0.01 suggested by Cheung and Rensvold (2002), indicated no significant improvement in the model fit indices. These test results conclude that CMB is not a concern in this study.

Table 3
Profile of the case study interviewees.

Management Level (Designation)		No. of Interviews	
		Archroma Case	Rockcheck Case
Top Management			
- General Manager		1	–
- Deputy General Manager		1	1
Middle Management	Functional Department		
- Senior Managers	- Production Department	1	1
	- Quality Department	1	1
	- Environment Department	1	1
	- Purchasing Department	2	1
	- Marketing Department	1	1
	- Culture & Publicity Department	–	1
Total No. of Interviews (15)		8	7

5.2. Construct validity and reliability

Table 4 shows the results of assessing construct validity and reliability. All the Cronbach's alpha values are above 0.7 and composite reliability (CR) above 0.6, indicating acceptable internal consistency across construct measures. The convergent validity is first established by examining the factor loadings: all are greater than 0.5 (Hair, 2009). The average variance extracted (AVE) values are all above 0.5, except for IMS. Given that IMS captures four management systems of diverse foci, its AVE value of 0.48, slightly below 0.5, is considered acceptable (Prajogo et al., 2021). The discriminant validity is established as all the square-rooted AVE values are greater than the correlations between constructs (Fornell and Larcker, 1981).

5.3. Hypothesis testing results

For survey data analysis, we employed covariance-based structural equation modeling (CB-SEM) using IBM® SPSS® Amos version 23. CB-SEM technique is widely used in organizational and management research, which allows simultaneous examination of the relationship between unobserved variables. We chose CB-SEM over partial least squares-based structural equation modeling (PLS-SEM) as the former is considered a preferred technique (Guide Jr. and Ketokivi, 2015) especially when its more restrictive assumptions related to data are met (Peng and Lai, 2012). Since our research model is grounded in well-established theory and seeks theory testing; sample size is relatively large (>200); model complexity is considerably low with normally distributed data; CB-SEM is an appropriate data analysis technique for this research as per Peng and Lai (2012)'s guidelines.

Hypotheses H1 and H2 on the antecedent role of CE culture ($\beta = 0.33$ at $p < 0.01$) and IMS ($\beta = 0.39$ at $p < 0.01$) for CM adoption are supported. Similarly, the direct effects of CM adoption on financial performance (H3) and environmental performance (H4) are also supported ($\beta = 0.34$ and 0.40 respectively at $p < 0.01$). These results are summarized in Fig. 2.

We employed the hierarchical regression analysis method to test the effect of I4.0 production technologies. As shown in Fig. 3 and Table 5, our results do not show any statistical support for the moderating role of I4.0 production technologies on the relationship between CM-to-firm environmental (H5a) and financial performance (H5b). Given this

Table 4
Construct analysis.

Construct/Variable		Items	EFA	CFA	α	CR	AVE
Circular Economy Culture (CEC)		CEC1	0.84	0.83	0.91	0.91	0.61
		CEC2	0.82	0.76			
		CEC3	0.90	0.93			
		CEC4	0.83	0.88			
		CEC5	0.85	0.86			
		CEC6	0.64	0.59			
		CEC7	0.65	0.59			
Integrated Management Systems (IMS)		IMS1	0.74	0.66	0.73	0.78	0.48
		IMS2	0.79	0.62			
		IMS3	0.76	0.72			
		IMS4	0.57	0.63			
Circular Manufacturing (CM)	Cleaner Production (CP)	CP1	0.81	0.81	0.91	0.66	0.50
		CP2	0.88	0.88			
		CP3	0.83	0.85			
		CP4	0.77	0.75			
		CP5	0.82	0.80			
	Circular Product Design (CPD)	CPD1	0.85	0.82	0.86		
		CPD2	0.84	0.90			
		CPD3	0.84	0.74			
		CPD4	0.73	0.68			
Industry 4.0 Production Technologies (IPT)		IPT1	0.72	0.60	0.86	0.86	0.55
		IPT2	0.83	0.83			
		IPT3	0.83	0.86			
		IPT4	0.74	0.61			
		IPT5	0.77	0.78			
				KMO = 0.87, Cumulative % of Variance = 68.13			
Firm Performance	Environmental Performance (EP)	EF1	0.85	0.83	0.93	0.93	0.72
		EF2	0.89	0.89			
		EF3	0.91	0.91			
		EF4	0.90	0.83			
		EF5	0.85	0.76			
	Financial Performance (FP)	FP1	0.83	0.77	0.94	0.95	0.75
		FP2	0.92	0.92			
		FP3	0.94	0.96			
		FP4	0.92	0.96			
		FP5	0.90	0.89			
		FP6	0.74	0.65			
				KMO = 0.88, Cumulative % of Variance = 78.49			

Correlations

Constructs	CEC	IMS	CM	IPT	EP	FP
CEC	0.78					
IMS	0.38**	0.69				
CM	0.48*	0.43**	0.71			
IPT	0.21*	0.32**	0.44**	0.75		
EP	0.21*	0.26*	0.32**	0.02	0.85	
FP	0.15*	0.20*	0.25*	0.21*	0.19*	0.86

$\chi2 = 925.27$ (df = 572); $\chi2/df = 1.61$; CFI = 0.946; SRMR = 0.059 and RMSEA = 0.049; *p-value <0.05, **p-value <0.01.

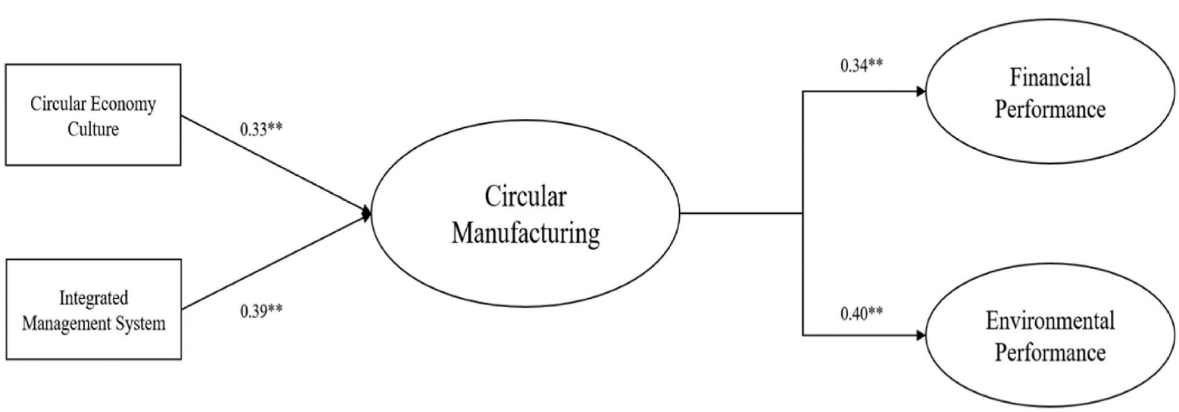

Fig. 2. Direct effects.

unexpected finding, we further tested the direct effects of I4.0 production technologies on firm performance and found a statistically positive effect on financial performance but not on environmental performance.

5.4. *Endogeneity test*

Reverse causality can be a serious threat to the validity of the

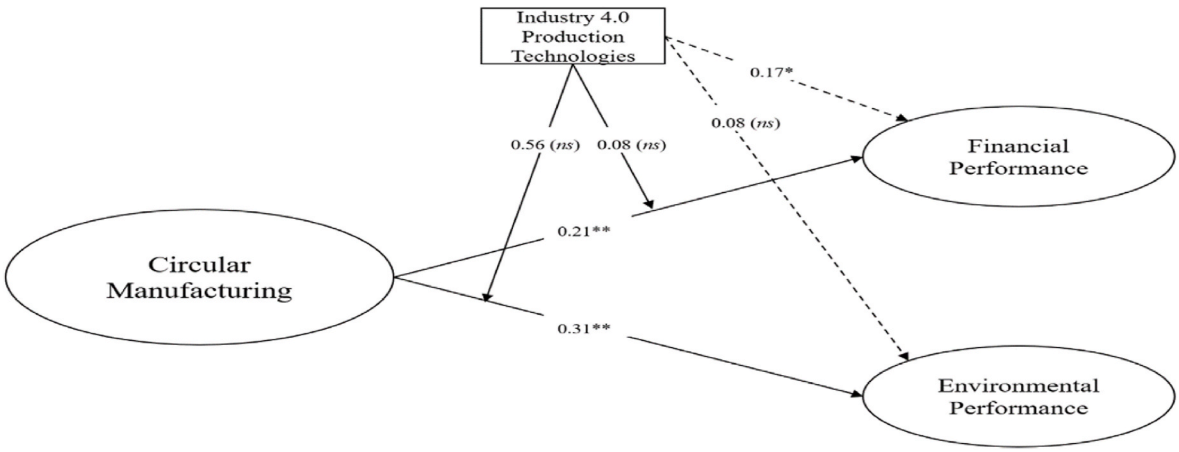

Fig. 3. Interaction effects.

Table 5
Hierarchical regression results.

	Direct Effects Model (1)	Moderating Effects Model (2)		
Control Variables	Financial	Environmental	Financial	Environmental
Ownership Type Dummy[a]				
Type 1	−0.18	−0.51	−0.28	−0.52
Type 2	−0.03	−0.25	−0.07	−0.25
Type 3	−0.09	−0.55	−0.20	−0.57
Type 4	−0.06	−0.19	−0.12	−0.20
Type 5	−0.09	−0.39	−0.19	−0.38
Firm Size Dummy[b]				
Size 1	0.03	−0.01	0.02	−0.07
Size 2	0.05	0.00	0.07	−0.04
Size 3	−0.02	−0.05	−0.03	−0.10
Size 4	−0.04	−0.15	0.01	−0.16
Size 5	0.07	−0.11	0.06	−0.10
Industry Dummy[c]				
Sector 1	0.05	0.08	0.06	0.07
Sector 2	−0.01	0.09	−0.04	0.07
Sector 3	0.06	0.17	0.06	0.14
Sector 4	0.04	0.06	0.05	0.03
Sector 5	0.19	0.07	0.18**	0.06
Sector 6	0.02	0.03	0.02	0.02
Sector 7	−0.03	−0.02	−0.03	−0.03
Sector 8	−0.03	0.12	−0.02	0.08
Sector 9	−0.10	−0.05	−0.10	−0.05
Sector 10	0.16	0.03	0.16**	0.02
Sector 11	0.11	0.22**	0.12	0.20*
Sector 12	0.20	0.13	0.20	0.16*
Main Variable(s)				
CM	0.34**	0.40**	0.21**	0.31**
IPT	–	–	0.17*	0.08
CM* IPT	–	–	0.08	0.56
R^2	0.24	0.26	0.20	0.18

*p-value <0.05, **p-value <0.01; Model (1) fit indices: $\chi 2$: 1662.07 (df = 1021); $\chi 2$/df = 1.63; CFI = 0.92; SRMR = 0.04 and RMSEA = 0.05; Model (2) F-Statistics: 2.23 and 2.05; the baseline for dummy variables include: "others" category for ownership type[a], "more than 8000 employees" for firm size[b] and "others" category for Industry[c].

theorized directional relationships between variables. In this research, there is a possibility that better financial performance drives CM adoption. Therefore, we conducted a two-stage least square (2SLS) regression analysis to assess endogeneity (Lu et al., 2018). In our data set, we found coercive pressure (DiMaggio and Powell, 1983) as a suitable instrumental variable because it is strongly correlated with the suspected explanatory variable but not with the disturbance term (Rossi, 2014).

In the first stage of the 2SLS test, we find a statistically significant correlation between coercive pressure and CM ($\beta = 0.29$ at $p < 0.01$). The second stage tests the effect of the predicted values from stage-1 on financial performance. The results are not statistically significant ($p > 0.10$). Following the Durbin–Wu–Hausman test procedures, we tested whether the error terms from the stage-1 model were correlated with the ones in the original model (Cameron and Trivedi, 2010). The results ($p = 0.97$) do not suggest any serious endogeneity problem. Appendix B presents the details of the 2SLS test results.

6. Case study results

6.1. Archroma case overview

Archroma is a global leader in color and specialty chemicals serving the branded and performance textiles, packaging and paper, coatings, adhesives, and sealants markets. The headquarter in Switzerland oversees the operations in over 100 countries involving approximately 2800 employees and 25 production sites. In 2018, Archroma promulgated its goal to achieve carbon neutrality in 2023 (37 years ahead of the Chinese government's 2060 deadline for the nation). In 2020, Archroma signed the United Nations Global Compact Statement from Business Leaders for Renewed Global Cooperation and the Global Coalition Call for Sustainability. In 2021, it was awarded the EcoVadis Platinum rating for its corporate social responsibility (CSR) performance.

As a subsidiary manufacturer in China, Archroma (Tianjin) Ltd. operates according to globally standardized management systems including ISO 9001, ISO 14001, ISO 45001, and ISO 50001. The company has established a sustainable management system and continually innovated in CM and related I4.0 production technologies. For these reasons, it was awarded the provincial level of "Green Factory" honor in 2020.

6.2. Archroma case study findings

We conducted eight interviews with Archroma (Tianjin), involving six senior managers and two senior executives in the production, environment, quality and purchasing departments. All interviewees agreed on the need for implementing CM. The general manager of Archroma (Tianjin) said, "Archroma is not only a leader in industry market, but also a leader in circularity and sustainability, which is our nature, the company's commission and the requirement of CSR". Consistent with our survey results, all interviewees indicated that their CE culture and IMS have positive effects on their CM implementation.

Archroma (Tianjin) has been in transition from a linear to a circular manufacturing system. The firm has embraced CM in both product design and production department. In practicing CPD, the company continuously develops products that are safe and designed to reduce natural resource consumption, thereby decreasing its environmental footprint. For example, the fluorine-based "C-8" chemical product is widely used in the high textiles market due to its excellent waterproof characteristic. However, the biodegradation cycle of this product is very long. Therefore, Archroma introduced C-6 products (Nuva® N) to substitute C-8 and gave up the highly lucrative C-8 market. The company also developed a fluorine-free waterproof product range (Smartrepel®) to offer an even more ecological option. Additionally, to avoid the use of the cancerogenic chemical of CAS 101-77-9, Archroma introduced the new product Cartasol® Yellow M-GLC liq to substitute Cartasol® Yellow M-GLA liq.

In line with the "12 Principles of Green Chemistry", Archroma has improved and innovated the manufacturing processes of azo-dyes, chemical additives, and "Nuva® N" waterproof products. The new processes minimized the use of energy, resources and chemicals, reduced waste and greenhouse gas emissions, and avoided unintended contaminants of raw materials and intermediates in the final product.

The environment department manager stated, "in addition to 'Safe' and 'Efficient', Archroma's third innovation pillar is 'Enhanced' performance and sustainability". These innovations on CM have a significant indirect impact on enhancing product value throughout the supply chain. The products with high value are more durable (and more appreciated by their users) than the less expensive ones. The general manager said, "The Archroma systems and solutions create value down the chain and deliver enhanced value to our customers, which guarantee the sustainability of the company's profit".

6.3. Rockcheck case overview

As an integrated iron and steel manufacturing enterprise, Rockcheck was founded in 2001. It is a subsidiary of Rockcheck Group Co., Ltd., which ranked No. 115 in the top 500 Chinese manufacturers and No. 99 in the top 500 Chinese private enterprises in 2021. It has around 4000 employees.

With substantial experiences in implementing I4.0 production technologies, Rockcheck has established strict environment principles and advanced management systems such as ISO 9001, ISO 14001, GB/T 28,001, and GB/T 23,331. Rockcheck was awarded the national "Green Factory" honor in 2019 and passed the audit of ultra-low emissions of environmental protection in 2021. Rockcheck set a goal to achieve peak carbon dioxide emissions in 2023 (seven years ahead of the nation's target 2030).

6.4. Rockcheck case study findings

We conducted seven interviews with Rockcheck including one executive (vice president) and six senior managers in six departments – production, purchasing, marketing, environment, energy, and culture & publicity. They stated that the company was confronted with many challenges and pressures in managing its environmental performance. The iron and steel sector, a significant contributor to pollution and greenhouse gas emissions, is under strict regulations on the annual output and emission level set by the national government in China. The sector in China is classified into three levels (A, B and C) based on the technologies used in their manufacturing processes and environmental control and performance. Only A-level companies are allowed continuous production under severe air conditions such as fog and haze. Therefore, to ensure sustainable and undisrupted production, Rockcheck, as a B-level company, has implemented many initiatives on CM and environmental protection, aspiring an upgrade to A-level.

Since 2001, Rockcheck has further emphasized the core management principle of "green driven" and has invested over 5.5 billion RMB on CM and environment initiatives. "There is no budget limitation on environmental investment and expenditure", said by the VP and one senior manager from the environment department. Interviewees from environment and production departments affirmed that their CE culture significantly promoted CM implementation and their IMS contributed to ensuring process control of CM and its environmental performance.

As a principle with top priority, environmental protection has been implemented throughout CPD, production process reengineering and operations innovation. Technology innovation and CPD have enabled Rockcheck to increase the use of recycled scrap steel for steel production, which is not only environment-friendly but also economically profitable. Many CP projects reduced gas emissions and waste discharge, while some other ones recovered value from coal gas, heats, steam, water discharge and solid waste. For example, using the coal gas and heats generated in production, the self-power generation project can meet around 60 percent of the company's total electricity needs. Rockcheck also achieved 100% comprehensive utilization of solid waste. Furthermore, Rockcheck was awarded many honors due to its zero-wastewater discharge initiative since 2008, which met all the company's water demand for manufacturing by purifying wastewater from itself and the local communities.

7. Discussions

7.1. Discussion of the study results and findings

Our survey results confirm that CE culture and IMS are major antecedents of CM implementation. Similarly, CE culture and IMS strengthened CM implementation in both case companies. These findings are consistent with previous studies suggesting that corporate cultures strongly influence innovations (Wang et al., 2021) and firms with strong sustainability cultures are likely to adoption sustainability practices (Marshall et al., 2015; Pagell and Wu, 2009). Similarly, IMS have been reported to significantly contribute to operational improvements and superior performance (Porter, 1996; Villena et al., 2021). Both case companies have a strong cultural orientation toward circularity and sustainability principles, and both are committed to take further steps (including CM initiatives) to comply with local regulations and customers' requirements relevant to environmental protection and CE. IMS, especially ISO 14001, play a critical role in the CM activities and ensure CM operations are performed in line with the international standards, customers' requests besides satisfying legal requirements. Hence, the role of IMS is not only as an enabler of CM, but also an assurance and subsequent control for CM implementation.

Results of the survey study affirm that CM improves long-term financial performance apart from environmental benefits. Likewise, interview participants from both case companies concur that CM implementations has led their firms to improvement in environmental and financial performance. This is a significant finding because previous studies have reported contradicting findings on the link between CE practices and economic performance. As mentioned earlier, Zhu et al. (2010, 2011) reported a positive link, but Genovese et al. (2017) and Nasir et al. (2017) questioned the economic viability of CE implementation due to the required upfront investments. Our mixed-methods approach provides a holistic understanding to reconcile the seeming contradiction: CM initiatives may indeed have a negative impact on short-term economic performance owing to substantial initial investments required for their implementation. However, CM initiatives offer long-term financial benefits resulting from reduced energy cost, materials reuse/recycling, and marketing advantages. With regards to economic performance of CM, Archroma's top management shared that their company not only complies with local environmental regulations, but also ensures consistency of practice within the global framework, which inevitably leads to discontinuation or substitution of some products although they are still profitable in the local market. The general manager said, "Archroma's commercial strategy is focusing on the promotion of more sustainable solutions, which accounted for 51% of Archroma' sales in FY 2022. We believe the number will be boosted significantly in the years to come." Similarly, Rockcheck's top management believes that their CM projects do not undermine their cost competitiveness since all companies in the iron and steel sector in China must invest in CM to meet the increasingly stricter environmental standards. Furthermore, both case companies confirmed that investing in CM brought benefits in terms of marketing and customer retention. A senior manager from the marketing department said, "The CM initiatives help with customer retention and keeping our market share, which are crucial."

Moreover, our survey study findings suggest that I4.0 production technologies do not moderate the relationship between CM and firm performance although they have direct and positive effects on financial performance. This finding corroborates Lin et al. (2019)'s analysis, which is based on secondary data, that I4.0 significantly improves the financial performance of manufacturers in China. Our case study suggests that both companies had widely adopted I4.0 production technologies such as intelligent manufacturing, IoT and big data analytics intending to achieve process automation and operational excellence (e.g., process simplification, operations optimization and productivity improvement) and to efficiently monitor and control energy use, waste, emission, and effluent. Such technologies enabled higher utilization of materials and energy besides reducing environmental accidents and improving environmental performance by strengthening the environmental supervision. Moreover, both firms claimed to have achieved good return on investments (ROI) in I4.0 production technologies due to productivity gains. In addition, the interviewees indicated that the effects of technology investments on performance decrease progressively – i.e., the marginal benefit is diminishing. Discussions and deliberations with the case study participants revealed that performance was mainly driven by practices not technologies, which shed light on the reason why the I4.0 production technologies did not show a moderating effect on the CM-to-firm environmental and financial performance relationship. This aligns with Tortorella et al.'s (2019) finding that the moderating effect of I4.0 on the lean production-to-operational performance is mixed, contingent upon the employed technology types and process practices. Our results support their argument that purely technological adoption does not guarantee better performance. Firms employing same CM practices are likely to achieve similar performance regardless of their differences in technology adoption. Therefore, organizations should focus on technologies and practices that aid systematic process improvements (Dalenogare et al., 2018).

7.2. *Theoretical contributions*

This study offers two important theoretical contributions. *First*, this study theorizes what constitutes CM. The term CM has been increasingly used but not clearly defined, which undermines the academic rigor of further studies on the topic. This research establishes CM as an extension of the cleaner production concept according to the design thinking of the CE. It operationalizes CM as a strategy which integrates CPD and CP. Our survey results prove that it is more appropriate to model CM as a second-order construct instead of treating CPD and CP separately for understanding performance implications. Our case studies provide concrete evidence that the joint exercise of CPD and CP was instrumental in improving circularity in manufacturing systems.

Second, this study provides strong empirical evidence on the explanatory power of PBV (Bromiley and Rau, 2014, 2016) in the CE context. Our survey study demonstrates that PBV is a useful theoretical lens for explaining the performance outcomes of CM practices that are imitable, available in the public domain, and transferable across firms. The case studies further establish that it is indeed practices that drive performance, not only in the direct effect of CM, but also in the lack of moderating effect of I4.0 production technologies on the practice-to-performance relationship.

7.3. *Practical implications*

Our study findings have important practical implications. *First*, based on our study results we suggest manufacturing firms to continuously nourish a CE culture and IMS to promote and strengthen CM adoption. Although organizational culture is intangible, it plays a fundamental role in shaping employee values and decision-making behaviors related to sustainability practices (Pagell and Wu, 2009). In the CE context, Burke et al.'s (2021) empirical study suggests that sustainable organizational values and CE vision make up the cornerstone of a successful CE implementation. Since leadership plays a crucial role in driving sustainability (Jia et al., 2019), the firms' top management should actively cultivate a CE culture for CM adoption. On the other hand, IMS use institutional procedures to ensure CE principles are incorporated in the manufacturing systems. They help to sustain CM adoption, which will further contribute to operational improvements and superior performance (Villena et al., 2021). In this regard, we advise the managers to follow strict compliance with the respective standards of IMS currently in place beside preparing for the implementation of the forthcoming ISO standards for CE, which are expected to be published by early 2024 (ISO, 2022).

Second, for the development of CM strategy, our conceptualization of CM provides a timely and practical guidance to the practitioners. In this regard, we advise practitioners to develop inter-functional coordination between product design function and production function to ensure CM is being exercised as a uniform strategy. Previous studies have also stressed on the importance of inter-functional coordination for CE, see for example, Burke et al. (2021). Additionally, external integration across supply chain actors to enable the take-back of end-of-use products for value recovery (i.e., to realize circularity of materials in the manufacturing supply chain through remanufacture, refurbish, reuse of parts/components/materials, recycling) would also be required. Luthra et al. (2022) provide a good example for external integration for circularity.

Third, the practitioners should confidently implement CM strategies relying on our empirical results which confirm positive environmental and financial performance outcomes. The implementation of CM comes with a potentially high cost in the short-term, as is the case with CE in general (Geng et al., 2009). However, it can reduce energy costs by improving energy efficiency and recovering energy from waste. It can also reduce material costs by reuse and recycling. Furthermore, there are marketing advantages associated with CM implementation by demonstrating a firm's commitment to environmental protection, which enhances firm reputation and helps retain existing customers and attract new customers. In the Chinese context, CM implementation in the most polluting industries like steelmaking will help reduce forced shutdowns which are very costly. Given that many manufacturers struggle with the upfront investments required, the government should consider financial aid in various forms including interest-free loans, environmental subsidies, and tax benefits to support CM implementations.

Fourth, firms should exercise discretion in their adoption of advanced technologies given that our study results strongly favor practices and processes as the main drivers of firm performance. Technologies often play a role in process improvements, but their impacts on performance are contingent upon many factors including implementation cost, technology type, and process characteristics (Tortorella et al., 2019). Therefore, we recommend that firms tailor technology solutions to their unique situations to ensure a strong ROI and performance improvements. In addition, manufacturers should be prepared for the fact that it takes time to fully exploit the potential benefits of I4.0 production technologies because they increase technical complexity and require employee training in new knowledge and advanced skills. Hence, I4.0 adoption can be demanding of financial resources (Kiel et al., 2017), particularly at the early adoption stage. Therefore, firms should strategically manage the short-term costs and long-term productivity gains from potential technology adoptions.

Last, the government should continue to enforce stringent environmental regulations to promote CM implementation. Our case studies reveal that environmental regulations level the playing field for all manufacturers in the same industry to embrace CM initiatives – the early movers did not have to worry about being economically disadvantaged because all their domestic competitors would have to incur a similar cost in comparable environmental initiatives. Therefore, environmental legislations and their strict enforcement are crucial for driving CM implementations. From a global perspective, there exist great disparities in environmental laws and their enforcement in different countries. Policymakers should not be shortsighted by sacrificing environmental protection for promoting economic development, noting that enforcing CM enhances the long-term financial performance of the industry.

8. Conclusion

While many manufacturers have made efforts to embrace CE to improve sustainability, it remains unclear what constitutes CM and how to operationalize it. The term CM has been increasingly used but not clearly understood, which undermines the significance of this potentially high-impact research area. Such a knowledge gap hinders CE research and practice. Earlier studies suggest that sustainability practices have a positive impact on both environmental and financial performance. However, in the CE context, there exist contradicting findings on the economic performance of CE implementation. This research focuses on CM, a key component of CE, to investigate its antecedents and performance outcomes, as well the moderating role of I4.0 production technologies on CM-to-firm environmental and financial performance. Our theoretical lens, the PBV, is rooted in the operations management discipline and precisely fits the need to examine performance implications from adopting practices that are replicable across firms.

This study employs a rigorous mixed-methods approach. We first conducted a large-scale survey among Chinese manufacturers and then two representative case studies for the triangulation and interpretation of survey results. The research is believed to be the first attempt to theorize and operationalize CM by extending the well-established CP concept according to the design thinking of CE. It provides empirical evidence that CE culture and IMS were antecedents to CM adoption. It confirms that CM adoption not only improved environmental performance but also long-term financial performance. However, I4.0 production technologies did not moderate the CM-to-firm environmental and financial performance relationship although they did lead to better financial performance. Both the survey study and case studies proved the explanatory power of PBV in the CE context. Based on the study findings, we derived several important practical implications for policymakers and practitioners.

Our study has several limitations which can be overcome in future research. *First*, this research applied the PBV to study environmental and financial performance. Future research may consider other performance aspects, for example, social sustainability performance. *Second*, our survey collected cross-sectional data. Future studies may attempt to collect longitudinal data to provide a more holistic view on the developments in the related research phenomenon. *Last*, our study context is China. It will be meaningful to conduct comparative studies in other countries.

Data availability

Data will be made available on request.

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Appendix A. Survey questionnaire

Variables and their measures		Sources
Circular Economy Culture (CEC)		Garza-Reyes et al. (2019)
(1: Strongly disagree – 5: Strongly agree)		
CEC1	Our company has formulated a circular economy strategy	
CEC2	Our company has a functional structure in charge of the circularity/CE practices	
CEC3	Our company’s management is committed and involved in circularity/CE	
CEC4	Our company’s shareholders and investors are involved and support circularity/CE	
CEC5	Our organization is developing the circular economy as a culture	
CEC6	Our company assigns a yearly budget for environmental expenditures	
CEC7	Our company creates and shares annual environmental reports with stakeholders	
Integrated Management Systems (IMS)		Villena et al. (2021); (Zhu and Sarkis, 2004)
(1: Not at all – 5: To full extent)		
IMS1	ISO 14000 serial certification	
IMS2	ISO 9000 serial certification	
IMS3	Total quality management type programs	
IMS4	Lean/Just-in-time systems	
Cleaner Production Practices (CP)		Sousa-Zomer et al. (2018); Zeng et al. (2010)
(1: Not at all – 5: To full extent)		
CP1	Improve employee environmental consciousness through training and evaluation	
CP2	Improve processes to reduce/eliminate waste	
CP3	Improve processes to increase energy efficiency through the use of clean technologies	
CP4	Increase investment in equipment for environmental protection	
CP5	Environmental issues are considered in the processes of production planning and technology innovation	
Circular Product Design (CPD)		Brezet (1997); Zhu et al. (2011); den Hollander et al. (2017)
(1: Not at all – 5: To full extent)		
CPD1	Design of products for re-contextualizing, re-purposing, repair, refurbishing, remanufacturing	
CPD2	Design of products for recycling	
CPD3	Design of products for ease of disassembly	
CPD4	Design of products to use recycled materials	
Industry 4.0 Production Technologies (IPT)		Tortorella and Fettermann (2018); Tortorella et al. (2019)
(1: Not at all – 5: To full extent)		
IPT1	Production process automation with process control sensors	

(*continued on next page*)

(*continued*)

Variables and their measures		Sources
IPT2	Remote monitoring and control of production processes through systems such as Manufacturing Execution Systems (MES) and Supervisory Control and Data Acquisition (SCADA)	
IPT3	Integrated systems for product development and product manufacturing	
IPT4	Simulations/analysis of virtual models (finite elements, computational fluid dynamics, etc.) for product design and commissioning	
IPT5	Collection, processing and analysis of large quantities of production process data (Big Data)	
Financial Performance (FP)		Flynn et al. (2010)
(1: Substantially lower – 7: Substantially higher)		
FP1	Growth in sales revenue	
FP2	Return on sales	
FP3	Growth in profit	
FP4	Net Profit Margin	
FP5	Return on investment (ROI)	
FP6	Growth in market share	
Environmental Performance (EP)		Yang et al. (2013); Zhu et al. (2011)
(1: Substantially lower – 7: Substantially higher)		
EP1	Emission of greenhouse gases (e.g., CO2, SOx, NOx …)	
EP2	Waste water (e.g., sewage)	
EP3	Other wastes (e.g., oily waste, sludge and rubbish)	
EP4	Total amount of hazardous and toxic waste	
EP5	Consumption of hazardous/harmful/toxic materials	

Appendix B. 2SLS endogeneity test

Variables	(1) Circular Manufacturing	(2) Financial Performance
Controls		
Ownership Type		
Type 1	−0.10	−0.22
Type 2	−0.13	−0.03
Type 3	−0.08	−0.14
Type 4	−0.12	−0.07
Type 5	−0.06	−0.13
Firm Size		
Size 1	−0.05	−0.02
Size 2	−0.12	0.01
Size 3	−0.03	−0.06
Size 4	0.03	−0.03
Size 5	0.08	0.05
Industry		
Sector 1	−0.09	0.07
Sector 2	0.02	−0.03
Sector 3	−0.05	0.06
Sector 4	−0.12	0.04
Sector 5	−0.13	0.20**
Sector 6	−0.06	0.02
Sector 7	−0.06	−0.02
Sector 8	0.06	−0.03
Sector 9	−0.03	−0.09
Sector 10	−0.14*	0.16*
Sector 11	−0.12	0.11
Sector 12	−0.08	0.22**
Main variable		
Circular Manufacturing	–	0.14
Coercive Isomorphism	0.26**	–
R^2	0.17	0.12

*p-value <0.05, **p-value <0.01.

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