Overcoming barriers to circular product design

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Abstract

The circular economy concept provides sustainability research with a new vision in place of the present linear economic model. This study focuses on product design, the starting point of applying circular thinking in supply chain functions. We investigate barriers to circular product design from a stakeholder perspective. Using thematic analysis and data collected from 15 semi-structured interviews in New Zealand, we identify four prominent barriers: financial constraints, inadequate infrastructure, government inaction, and global market barriers. The most influential stakeholder classes for overcoming the barriers are consumers, industry leaders, and governments. Circumventing measures lie in sustainable end-of-life product and waste management, resource circularity, modularity and standardization in design, and supply chain collaboration. Based on these new insights, we develop a roadmap for circular product design, providing practical guidance for businesses and policymakers. We also add to research on stakeholder theory by exploring its descriptive aspect in the context of a transition to circular economy at the supply chain level.

Keywords: Circular economy; Circular product design; Barrier; Circular supply chain management; Closed-loop supply chain

Article Classification: Research Article

1. Introduction

Climate change, resource depletion, and loss of biodiversity are imminent threats that have sparked worldwide concern about environmental sustainability. Over the decades, policymakers, researchers, and business practitioners have continuously searched for solutions to sustainable development. One school of thought focuses on the circular economy (CE) promoted by MacArthur (2013). CE concentrates on maximizing the circularity of resources and energy within production systems by establishing the restorative cycle (e.g., reuse/repair/remanufacturing/refurbishing) and regenerative cycle (e.g., biological transformation by composting/anaerobic digesting/cascading) (Ghisellini et al., 2016; MacArthur et al., 2015). CE emphasizes a zero-waste vision through this circulation of resources, providing an innovative prospect to deal with sustainability challenges (Zhang et al., 2019).

Supply chain management research has increasingly incorporated the CE concept to maximize the circular resource flows at the supply chain level (Goltsos et al., 2019; Govindan & Hasanagic, 2018). Genovese et al. (2017) find a clear positive environmental impact when integrating CE principles with long-debated sustainable supply chain management practices, evidencing the promising outcomes of CE under growing sustainability pressures. Genovese et al. (2020) call for more research on the transition toward CE from a supply chain perspective, especially in the context of closed-loop supply chains. 'Circular supply chain management' is one such research stream and focuses on systematically integrating supply chain operations, from product/service design to end-of-life, and waste management to restore technical materials and regenerate biological materials across different supply chains (Farooque, Zhang, Thürer et al., 2019). It should be noted that the concept of circular supply chain management is an extension of the concept of closed-loop supply chain management (Souza, 2013), because it is typically unrealistic to reuse all materials within an immediate (i.e., closed-loop) supply chain. Circular supply chain management encompasses closed-loop supply chain practices (Zhang, Wang et al., 2021). Still, it may go further in improving resource circularity by collaborating with different supply chains within and/or outside of the same industry sector (Farooque, Zhang, Thürer et al., 2019). Therefore, in this paper, we use the term circular supply chain management, but acknowledge its root in the concept of closed-loop supply chain management.

CE emphasizes the sustainability impact of products and resources in their end-of-life cycles. However, this impact heavily depends on the design and conception phase, that is, the early stage of production (Kobayashi, 2006). It is difficult to change resource allocation and infrastructure after design, and thus, a circular production system is unlikely to be established unless environmental measures are taken during product design (Bocken et al., 2016). Therefore, 'circular product design' is a foundational step to CE and circular supply chain management.

The extant literature has widely studied the barriers to CE and circular supply chain management and their circumventing measures at the strategic level (e.g., business model innovation) (Govindan & Hasanagic, 2018; Mangla et al., 2018; Zhang et al., 2019). However, there is little research at a product design level. The strategic transformation of firms to manage a circular resource flow requires concurrent upgrades of the design strategies. For instance, supply chain collaborations on 'remanufacturing' must be supported by design for disassembly. The lack of knowledge on circular product design impedes firms' transition to CE. Given the strategic importance of circular product design, this research explores the barriers to circular product design and their circumventing measures. It employs a qualitative approach to fit the exploratory nature of the research due to the lack of relevant studies.

We adopt stakeholder theory (Freeman, 1984) as the theoretical lens for this study. As a novel and complex production model, CE and circular supply chain management requires systematic operations of multiple stakeholders, and may create new stakeholder relationships (e.g., new customers and suppliers for waste and by-products). Stakeholder theory, especially its instrumental and descriptive aspects, underpins the analysis of the barriers and the circumventing measures from a stakeholder perspective. The analysis of stakeholder legitimacy, power, and urgency supports the exploration of stakeholder classes relating to the identified barriers. By primarily dealing with the most prominent stakeholder, firms can improve their efficiency in operationalizing circular product design.

We seek to fill the research gap on circular product design by focusing on the following objectives:

- To understand the key barriers to circular product design and the circumventing measures from a stakeholder perspective
- To identify prominent stakeholder groups who are most influential in overcoming the identified barriers

We employ a thematic analysis of 15 semi-structured interviews conducted in New Zealand, a country known for its clean, green image and strong environmental protection culture. We identify major barriers to circular product design, including *financial constraints, inadequate infrastructure, government inaction*, and *global market perspectives*. We find that *consumers, industry leaders*, and *the government* are the most salient stakeholder classes that have strategic impacts on overcoming these barriers. In terms of circumventing measures to overcome these barriers, effective practices are modularity and standardization design, sustainable end-of-life product and waste management, resource circularity, and extended collaborations in supply chains. Furthermore, we develop a roadmap for circular product design that encompasses these critical factors at macro, meso, and micro levels. The roadmap provides businesses and policymakers with practical guidance to advance circular product design and CE.

Our study complements the CE literature by providing novel insights into circular product design. From a product design perspective, we find that the specific barriers, circumventing measures, and stakeholder impacts are interrelated with those identified by previous studies from a strategic perspective. Our findings provide firms with guidance on the barriers and stakeholder classes that should be strategically and primarily dealt with in a successful transition to CE. The stakeholder impact specific to circular product design found in this study indicates that a broader stakeholder perspective should be considered in CE adoptions. We contribute to stakeholder theory by exploring its descriptive aspect in the context of supply chain implementation of circular product design. Our findings highlight the importance of stakeholder classes, adding understanding to the application of stakeholder theory in the CE literature.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature on circular product design and its barriers to CE and circular supply chain management. Section 3 explains the research methodology and data collection procedures. Section 4 presents the empirical study results, analysis, and findings. Section 5 discusses policy and managerial implications. Section 6 concludes the research.

2. Literature review

2.1. Theoretical background

2.1.1. Stakeholder theory

This paper adopts stakeholder theory, an approach that is concerned with the reciprocal relationships between firms and their numerous stakeholders, where firms can achieve business success by taking stakeholders' interests into account (Donaldson & Preston, 1995). Freeman (1984) defines a stakeholder as any group or individual who can affect or who is affected by the achievement of the organization's objectives. Major stakeholders include organizations, employees, customers/consumers, suppliers, competitors, governments, communities, activist groups, and trade associations (Donaldson & Preston, 1995; Jawahar & McLaughlin, 2001).

The stakeholder theory illustrates the firms' relationship with these stakeholders by referring to three aspects: instrumental, descriptive, and normative (Donaldson & Preston, 1995). The instrumental aspect of stakeholder theory demonstrates the benefits of firms managing stakeholder relationships (Jones, 1995). Firms stand to gain by investing in the creation and maintenance of relationships with stakeholders. The descriptive element of stakeholder theory emphasizes the importance of stakeholders, categorizes them, and considers how firms take into account stakeholder interests (Jawahar &

McLaughlin, 2001). It also suggests how firms can manage various stakeholder relationships. The normative aspect of stakeholder theory presents the moral or philosophical reason why firms should consider stakeholder interests. The normative reason for firms' environmental and social concerns remains ambiguous (Donaldson & Preston, 1995). In this study, we focus on the instrumental and descriptive aspects of stakeholder theory to explore the barriers to circular product design and their prominence from a stakeholder perspective.

Mitchell et al. (1997) propose that the salience of a stakeholder group to a firm relies on stakeholder power, legitimacy, and urgency, which can be used to identify the different classes of stakeholder groups in a firm's environment. Stakeholder power relates to the degree to which a stakeholder group can influence a firm's operations, which is decided by the firm's dependence on the stakeholder group for resources. Stakeholder legitimacy indicates the normative principle of stakeholders' requests. The legitimate requests are consistent with a generalized perception of desirable, proper, or appropriate social values, beliefs, and definitions. Stakeholder urgency identifies the timely scale of a stakeholder group's claim, showing the requested degree of a firm's immediate response to the stakeholders' requests. The most salient stakeholders should have a high degree of power, legitimacy, and urgency. The firm's adherence to these stakeholders creates the highest financial performance as well as a competitive market position (Busse, 2016).

The stakeholder theory has been widely applied in supply chain management research. In studying sustainable supply chain management practices, the stakeholder theory is used as the theoretical lens to understand the coercive stakeholder force, specifically, customer firms' stakeholder pressure on their suppliers' adoption of sustainable operation (Seles et al., 2016; Villena & Dhanorkar, 2020). In the CE context, Govindan and Hasanagic (2018) applied the instrumental aspect of the stakeholder theory to explore drivers, barriers, and practices relating to various stakeholders. In our study of the barriers to circular product design, the instrumental stakeholder theory supports us in developing a systematic framework that incorporates these barriers categorized by stakeholder groups. Firms can effectively identify the specific stakeholder groups and manage their relationships to overcome the associated barriers. The descriptive stakeholder theory underpins our analysis of the top stakeholder class in the firms' proactive adoption of circular product design. Firms can improve their operational efficiency by strategically allocating resources to deal with the most prominent stakeholder classes.

2.1.2. Circular economy and circular supply chain management

Circular product design is developed with CE principles and requires a circular model at the supply chain level. This section introduces the concepts of CE and circular supply chain management to clarify the key aspects of studying circular product design.

CE is an alternative to today's dominant, linear take-make-dispose industrial model, where a cradle-to-cradle approach through regeneration (e.g., anaerobic digestion) and restoration (e.g., reuse/remanufacturing) allows for a cyclical flow of materials (MacArthur, 2013). Three CE principles are 'design out waste and pollution,' 'keep products and materials in use,' and 'regenerate natural systems' (Ellen MacArthur Foundation, 2017). CE substantially increases the rate of reuse, remanufacturing, and recycling, and thus the productivity of technical materials. The emphasis on using renewable materials and energy as well as organic wastes preserves natural capital (Jabbour et al., 2018). CE aims to create a self-sustaining production system with an infinite circularity of resources (Genovese et al., 2017).

Circular supply chain management aims to integrate supply chain operations to maximize the cyclical flow of resources and waste management in line with CE principles (Weetman, 2016). According to Farooque, Zhang, Thürer et al. (2019, p. 884), "circular supply chain management is the integration of circular thinking into the management of the supply chain and its surrounding industrial and natural ecosystems. It systematically restores technical materials and regenerates biological materials toward a zero-waste vision through system-wide innovation in business models and supply chain functions from product/service design to end-of-life and waste management, involving all stakeholders in a product/service lifecycle including parts/product manufacturers, service providers, consumers, and users."

There is a high interdependence between supply chain partners in terms of production and material uses in modern business (Tate et al., 2012), indicating that it is necessary to build a more complete circular system at the supply chain level. Circular supply chain management incorporates two supply chain designs (Genovese et al., 2017). First, it shapes traditional forward supply chain resource and information flows to a circular model. Supply chain partners collaborate to recover the value of wastes and regenerate biological nutrients by, for example, reverse logistics. Second, circular supply chain management supports collaborations to create resource circularity across different supply chains. The recoverability and regenerability of resources can be restricted by the scope of firms' immediate supply chains. A new customer-supplier relationship outside the immediate supply chain is required to maximize the circularity of resources (Angelis et al., 2018). These two supply chain designs develop system-wide circulation, which substantially improves the efficiency and effectiveness of closed-loop supply chains.

2.2. Barriers to CE and circular supply chain management

This subsection reviews the barriers to CE and circular supply chain management to inform the study of barriers to circular product design. Several recent studies (Farooque, Zhang, Thürer et al., 2019; Govindan & Hasanagic, 2018; Mangla et al., 2018) conducted very comprehensive reviews of barriers to CE and circular supply chain management. This study builds on their works and uses a narrative literature review approach to classify barriers from a stakeholder perspective to identify primary stakeholder groups. We also cover the circumventing measures. Table 1 provides a conceptual classification of the review results, which establishes the theoretical foundation for exploring the barriers and stakeholder impacts specific to circular product design.

Table 1. Barriers to CE and Circular Supply Chain Management

Barriers	Sub-barriers	Stakeholder Groups					Circumventing Measures
		Consumer	Government	Organization	Employee	Supply Chain Partners /Industry Association	
Financial and economic barrier	Cost of materials and labor			*X*			Actively exploring the economic benefits of the CE and support of shareholders/creditors
	Lack of working capital			*X*			
	High start-up costs			*X*			
Technological barriers	Lack of innovative technologies		*X*	*X*			Government support for technology transfer across countries and supply chains, innovative integration of existing technologies into CE
	Lack of technical expertise				*X*		
Commitment barriers	Poor leadership and management			*X*			Strategic thinking on the development of dynamic capabilities of CE, industry standardization on CE operations, development of organization-wide CE culture and engagement
	Lack of industry-specific training and monitoring programs					*X*	
	Employee resistance				*X*		
Legislation and policies barriers	Lack of CE favorable taxation		*X*				Performance-based taxation and incentive system and financial instruments by governments, legislation on extended producer responsibility
	Lack of funding to CE businesses		*X*				
	Lack of a systematic CE framework		*X*				
Society barriers	The concerns with performance/quality/safety of 'CE products and services'	*X*					Shared responsibility by consumers in the CE system, development of practical preference by consumers to 'CE products and services,' CE education on consumers.
	Low consumer participation in the circular process at the end of the product life cycle	*X*					
	Unawareness of the importance of environmental issues	*X*					
Operational barriers	Lack of infrastructure for reverse logistics and disassembly activities				*X*	*X*	Innovative supply chain collaboration and integration for circular resources flow, a proactive approach to managing resource circularity and integrating it into production planning and control system
	Unaligned supply chain design for a circular system				*X*	*X*	
	Challenges in operational decision-making				*X*	*X*	

We discuss six major barriers to CE and circular supply chain management identified in the literature: *financial and economic barriers, technological barriers, commitment barriers, legislation and policy barriers, society barriers,* and *operational barriers.*

Financial and economic barriers are the biggest challenge in CE implementation, including the *cost of materials and labor, lack of working capital,* and *high start-up costs.* Radical changes in the present linear model aimed at creating a circular system require immediate and significant financial and cultural investment, including purchasing costly sustainable materials, training staff, implementing new technology, and developing infrastructure (Govindan & Hasanagic, 2018). Over the decades, the pursuit of operational efficiency (e.g., leanness) means that firms are unlikely to have the sparse working capital to support such investments (Zhu & Geng, 2013). Moreover, the economic returns to CE investment are more likely to be in the long term, while firms bear high start-up costs (Ormazabal et al., 2018). It takes time to reach the fruition of CE, as it requires long-term involvement to develop the sustainability markets and cost-efficiency gained from the capacity of regeneration and restoration (Govindan & Hasanagic, 2018).

From a stakeholder perspective, the financial and economic barriers are centered on '*organizations*' to develop circumventing measures. Organizations need to actively seek financial resources from, for example, shareholders/creditors to establish start-up investment in CE (Su et al., 2013). Meanwhile, organizations should actively explore the economic benefits of CE (Govindan & Hasanagic, 2018). Improved environmental accounting can substantially reduce firms' sustainability risk and associated costs, enable them to charge a premium price, and secure external funding.

The technological barriers focus on the *lack of innovative technologies* and *technical expertise.* The complexity of materials is increasing in order to fit ergonomic needs, which, however, restricts the technological flexibility to regenerate and recover the materials (e.g., packaging). Aggressive technology innovation is required to facilitate regeneration and restoration (Zhang et al., 2019). In addition, there is a lack of skilled and experienced labor resources to operate and maintain green technologies (Rizos et al., 2016). At present, staff training is most suited to long-standing linear operations and the use of associated technologies. Technical expertise on, for example, biological decomposition, is not widely available to support CE adoption.

Three groups of stakeholders, '*government,*' '*organization,*' and '*employee,*' are important to overcome these technological barriers. Governments can facilitate green technology transfer between countries and firms, and government financial incentives can substantially motivate technology providers to develop CE technologies (Geng & Doberstein, 2008). Moreover, given its macro-level position, a government is more likely to develop collaborations across different supply chains and industry sectors on biological transformation technologies (Genovese et al., 2017). From the organizations' perspective, they need to develop visionary thinking on CE. Some CE aspects do not rely on new technologies but instead the gradual evolution of processes and a systematic understanding of energy and resource flows (Govindan & Hasanagic, 2018). The strategies of ‘slowing resource loop,’ including repair/reuse/remanufacturing/refurbishing, can be realized by innovative business models that utilize the existing technologies (Bocken et al., 2016), which are more cost-efficient than recycling or biological decomposition. Employees should be provided with CE training to improve their capacity in exploring resource circularity. Importantly, a CE vision should be developed in the workplace, where employees are encouraged toward continual improvement, collaboration, and system thinking on circular resource flows (Rizos et al., 2016).

Commitment barriers refer to the lack of organization-wide knowledge and acceptance of CE practices, specifically, *poor leadership and management, lack of industry-specific training and monitoring programs,* and *employee resistance.* Management teams may not have an awareness of or interest in circular business practices due to few economic incentives (Mangla et al., 2018). The nature and operations of circular systems are not the same between industries (e.g., textile and electronics). However, CE training and monitoring programs for each specific industry have not been widely developed (Govindan & Hasanagic, 2018), adding difficulties in improving the knowledge and acceptance of CE. Moreover, the radical changes involved in establishing a circular operation disrupt the standardized working environment and pattern, and thus create additional workload; employee resistance is expected (Sizhen et al., 2005). It is challenging to build employee buy-in under such fundamental modifications in operations.

The major stakeholder groups involved in circumventing commitment barriers are ‘*organization,*’ ‘*employee,*’ and ‘*industry association.*’ The top management team needs to affirm the long-term business mission and commitment to CE (Ormazabal et al., 2018). Business leaders should adopt strategic thinking centered on developing firms’ dynamic capabilities for CE in the changing business environment (Farooque, Zhang & Liu, 2019). The improved CE leadership and management capacity can create organization-wide CE culture and engagement. Along with incentives and training, employee buy-in can be established in CE implementation. Industry associations can support the development of industry-specific training, information sharing, and performance measures in supply chains (Ormazabal et al., 2018). This can motivate the standardization of CE adoption across supply chains and thus improve the overall commitment to CE.

There are barriers relating to legislation and policies, including the *lack of CE-favorable taxations, funding to CE businesses,* and *a systematic CE framework*. The historical development in legislation, policy, and ideology is mainly based on a linear model, which creates an uneven ground for the CE model to compete with the established linear system (Mahpour, 2018). There is an urgent need to provide new and clear legislation and policies to support CE principles and to address CE-specific issues (Masi et al., 2018). Moreover, a systematic framework should be created by governments, where successful business models for CE can be showcased to other entrants, and performance measurement and policies can be continuously updated to enforce efficient and effective CE adoption (Govindan & Hasanagic, 2018).

'*Government*' is a significant stakeholder, widely found in the CE literature, in the top-down approach of CE adoption (Genovese et al., 2017; Govindan & Hasanagic, 2018; Mangla et al., 2018). Governments should establish performance-based taxation, an incentive system, and facilitate to create financial instruments by banks, which supports the investment of firms in CE adoptions (Geng & Doberstein, 2008). Governmental legislation on 'extended producer responsibility' can effectively stimulate CE implementation, where producers are taken into account for a product at the post-consumer stage of its life cycle (Zhu et al., 2014). The use of diverse instruments by governments (e.g., tax, bans, and regulations) can strongly contribute to firms' transformation to CE (Ghisellini et al., 2016).

Society barriers refer to the lack of awareness and uptake of CE from the consumption perspective, including *concerns with performance/quality/safety*, *low consumer participation in the circular process at the end of the product life cycle*, and *unawareness of the importance of environmental issues*. The demand for products with a circular nature remains a niche (Masi et al., 2018). The intrinsic preference of consumers for new products and services substantially hinders the development of markets for 'CE products and services.' One significant issue is that consumers' concerns with refurbished products in terms of performance, quality, safety, and health reduce their acceptance of these products (Govindan & Hasanagic, 2018; Zhu et al., 2014). Moreover, consumers' willingness to participate in the circular process at the end of the product life cycle is commonly low (Masi et al., 2018). Thus, the recyclability rate and the quality of recycling are challenging to manage. Finally, while there is an increase in public awareness of environmental issues, a society-wide acceptance of consumption changes in favor of the environment has yet to be established. These changes are radical and disruption to the status quo of living and consumption patterns (Mangla et al., 2018).

From a stakeholder perspective, the circumventing measures to these society barriers strongly rely on the '*consumer*.' A shared responsibility by consumer groups in the CE system should be developed (Govindan & Hasanagic, 2018). Consumers need to increase awareness of their importance in a circular resource flow through 'CE education.' It is crucial that consumers manage the waste at the end of the product life cycle, which is a key resource in the CE vision. This involves active consumer participation in returning used products. Moreover, practical preference by consumers for refurbished/remanufactured/reused products needs to be developed. The shift in purchasing pattern can substantially motivate producers' CE ambition.

The operational barriers include *lack of infrastructure for reverse logistics and disassembly activities, unaligned supply chain design for a circular system,* and *increased complexity in operational decision-making*. The present supply chain infrastructure is purposed to support the forward flow of materials and services. It is thus unable to underpin the comprehensive reverse logistics and disassembly activities that are critical components of material circularity (Govindan & Hasanagic, 2018). Moreover, the present supply chain design focuses heavily on efficiency (e.g., low cost and high speed) in line with the linear model (Pagell & Wu, 2009). The development of CE infrastructure and supply chain integration (e.g., a process of sharing restorable materials) within the same supply chain or across different supply chains remains sluggish (Ritzén & Sandström, 2017). Furthermore, circular resource flows substantially change the planning and operational decision variables in supply chains, requiring a more advanced production planning and control system (Govindan et al., 2015). The operations of remanufacturing/refurbishment and waste conversion in line with CE add complexity and challenges in scheduling, capacity planning, and inventory control. Thus, it becomes more difficult to manage supply chain cost efficiency.

'*Supply chain partners*' are the focal group of stakeholders to circumvent these operational barriers. A new type of supply chain collaboration (e.g., re-engineering) and shared responsibilities for circular resource flow is required (Ritzén & Sandström, 2017). A high level of supply chain integration by, for example, blockchain-enabled information flow can improve the efficiency in reverse logistics (Wang et al., 2020). Given the present linear supply chain design, most supply chains passively accept returned products from the markets; hence, the operational decision variables of remanufacturing are forcibly added into supply chain planning (Guide et al., 2003). A more proactive approach for collecting, disassembling, and remanufacturing needs to be developed (e.g., replacing product ownership with service offering). The scheduling, capacity, and inventory level in these operations can be flexibly managed in supply chains and integrated into the strategic decision-making of CE (Govindan et al., 2015; Guide et al., 2003).

2.3. Circular product design

The present product design philosophy tends to focus on the end-user's needs rather than the end-of-life options for the product (Bocken et al., 2016). In addition to customer-centric designs, planned obsolescence has become a commonly used design strategy to limit the lifespan of a product, and thus to encourage sales (Moreno et al., 2016). While these design philosophies and strategies are dominantly applied in the present production system, they lead to embedded resources being lost to the waste stream indefinitely.

Circular product design would allow products to become part of the waste solution rather than the problem (Preston, 2012). den Hollander et al. (2017) discuss the two elements underpinning circular product design: 'design for product integrity' and 'design for recycling' (both conventional and biocycling). While recyclability should be incorporated into product design, design for maintaining product integrity is important for preserving economic and environmental values. The three design components, long use (e.g., durability), extended use (e.g., maintenance), and recovery (e.g., refracturing), can be used in an order to decrease the destruction of product integrity (den Hollander et al., 2017).

Circular product design has evolved to incorporate a variety of concepts. Design for inner loops is one of these concepts, where products are designed to follow the inner loops of the CE butterfly diagram. The inner loops of the CE butterfly diagram promote design approaches such as reuse, sharing, cascading, remanufacturing, and refurbishment. This design strategy aims to slow, close, and narrow the resource cycle, which allows the resources embedded in products to remain in circulation for as long as possible (Bocken et al., 2016). Another concept is product life extension and long-life product design strategy. This strategy ensures that products are designed to be durable and long-lasting in order to prolong their usable lifespan. This strategy ensures products can be reused multiple times and by multiple users. Design for modularity is a design strategy that allows products to be easily repaired, remanufactured, and upgraded. This design strategy ensures the time length of product use can be maximized through upgrades and repair processes (Mestre & Cooper, 2017). Widely adopted eco-design substantially contributes to the development of circular product design. Eco-design systematically integrates environmental aspects into product design, leading to improved design specifications for a reduced environmental impact (Romli et al., 2015). However, eco-design retains linear thinking, while circular product design follows a circular model and focuses more on maintaining product integrity (e.g., remanufacturing is preferred to recycling) (den Hollander et al., 2017).

The two resource cycles that underpin CE, the biological and technical cycles (Jabbour et al., 2018), should also be embedded in circular product design. In the biological cycle, renewable and organic resources are primarily used in innovative product design. At the end of the life cycle of these resources, their nutrients can be safely returned to nature in a biomimicry process that emulates the natural process of resource generation. In the technical cycle, a restorative process should be enabled by the product design. The inorganic materials (e.g., plastic and metal) that do not naturally break down in anaerobic digestion can retain their value through remanufacturing, repair, and repurposing. The CE research has explored strategies for circular product design that support biological and/or technical cycles. Van den Berg and Bakker (2015) provide a systematic framework for the technical cycle based on circular product design, including 'future proof' (i.e., product-life extension), disassembly, maintenance, remake, and recycling. Sauerwein et al. (2019) focus on additive manufacturing or 3D printing for circular product design. The authors found additive manufacturing that uses mono-materials substantially supports recyclability, and its digital production enables a high degree of freedom in repairs and upgrades. However, the biological cycle is challenged by the durability and functionality of bio-materials used in additive manufacturing.

2.4. Summary of knowledge gaps

The above review of the literature reveals two major research gaps. First, previous studies on barriers to CE and circular supply chain management have primarily focused on the strategic level (e.g., business model innovation), while there has been little research on the product design level. Many challenges on re-engineering (e.g., efficient disassembly, remanufacturing, and reuse) at the end of the product life cycle are caused by the failure to apply CE thinking in the initial product design (Sabaghi et al., 2016). The product concepts, resource allocation, and infrastructure are difficult to change in the later stages of production after the design stage. Many CE business strategies (e.g., the product-service system) have been developed. The failure to study barriers to circular product design, however, impedes the operationalization of these strategies. A concurrent development at both product design and strategic levels can ensure a successful transition to CE.

Second, research on CE and circular supply chain management that adopt stakeholder theory mainly focus on the instrumental nature of stakeholders. The descriptive aspect of stakeholders has not been widely explored. Various groups of stakeholders that are instrumental to the success of CE adoption have been identified in the literature, providing firms with a multiple-stakeholder perspective to overcome different barriers (e.g., Govindan & Hasanagic, 2018). Nonetheless, little is known about the stakeholder classes. Following the descriptive stakeholder theory, stakeholders have different scales of importance to organizations, depending on their potential to satisfy critical and specific organizational needs (Donaldson & Preston, 1995; Jawahar & McLaughlin, 2001). Firms would do well to concentrate their resources on dealing with critical stakeholder groups, and thus improve operational efficiency in overcoming these barriers.

Our research seeks to fill these two research gaps. We adopt stakeholder theory to study the barriers to circular product design and the circumventing measures enacted by stakeholder classes.

3. Methodology

We use a qualitative approach to investigate our research questions. Specifically, 15 semi-structured interviews were conducted in New Zealand to collect qualitative data. We conducted a thematic analysis, following a systematic approach proposed by Braun and Clarke (2006), to analyze the data. Circular product design is still an emerging topic, and thus, the critical factors and their relationships that constitute it remain implicit and complex. Such complexities are best teased out through a qualitative approach, which can offer rich insights into this novel concept.

3.1. Data collection methods and sample

Fifteen semi-structured interviews were conducted in Auckland, New Zealand, in 2019. All the interviews were conducted face to face. Each interview took approximately 45-60 minutes. The participants included 11 senior managers and four active academic researchers of CE. To ensure data reliability and validity, we employed a purposive sampling (also known as purposeful or judgmental sampling) approach (Merriam, 2009; Saunders, 2019) to invite research participants from among those who were very knowledgeable on sustainability/CE and product design or supply chain management. We used the member directory of the 'Sustainable Business Network' to search for interview participants. The Sustainable Business Network represents a group of local businesses that embrace sustainable operations, including the CE vision. Our interview requests were sent to senior managers (e.g., general managers and operations managers) of the organizations, who had a wide breadth of knowledge on the firms' supply chain operations, the CE vision, and product design.

Table 2 reports the selected characteristics of the interview sample. The participants had a median value of nine years of working experience with sustainability and/or CE practices, showing a comprehensive knowledge background and practical experience relating to our research focus. The industries in the sample are distributed across diverse manufacturing and service sectors, including personal care product manufacturing, logistics services, packaging manufacturing, commercial flooring, and textile rental services. We also conducted interviews with four active CE researchers to incorporate relevant academic perspectives. These four researchers had an average of over ten years of working experience in the industry or consulting for governments and were well connected with the industry. Three of them had appeared in local media several times in recent years, using their subject expertise to speak on matters related to sustainability.

Table 2. Description of the Interview Sample

Job Positions	Industry/Discipline Sector	Years of Experience in Sustainability and/or CE
Director of Marketing and Digital	Personal care products manufacturing	17
Managing Director	Commercial flooring solutions	20
Business Manager	Textile rental services	7
Managing Director	Personal care products manufacturing	2
Managing Director	Packaging manufacturing	10
Business Manager	Logistics services	18
Operations Manager	Personal care products manufacturing	2
Marketing Manager	Logistics services	3
General Manager	Recycling services	9
Research and Development Manager	Personal care products manufacturing	25
General Manager	Personal care products manufacturing	2
Senior Lecturer	Academia in supply chain management & sustainability	6
PhD Researcher (formerly a university lecturer)	Academia in supply chain management & sustainability	9
Senior Lecturer	Academia in environmental engineering	20
Senior Lecturer	Academia in product design and sustainability	18

The interview questions were sent to participants prior to the interviews so that they could formulate and structure responses. The detailed interview questions are provided in the Appendix. We formulated these interview questions based on the theoretical foundation that we developed in the literature review section. Three conceptual aspects were embedded in the interview questions to extract data for thematic analysis. First, we followed stakeholder theory to focus on exploring the barriers from a stakeholder perspective. Thus, interview questions were designed to relate the identified barriers to participants' stakeholder groups. Second, using our conceptual classification of the barriers to CE and circular supply chain management (i.e., Table 1), we included major categories of barriers and stakeholder groups in the interview questions. Third, the descriptive element of stakeholder theory suggests the existence of various stakeholder classes in a firm's environment. We designed the questions to explore the prominent stakeholder groups and associated barriers in the context of circular product design. The interview questions were also designed to inductively capture unexpected factors and stakeholders. The participants were advised to discuss more aspects in addition to the pre-defined framework.

We carefully designed our interview protocol (Saunders, 2019) to collect the most relevant and reliable qualitative data. We introduced our research interest, background, and key information to the participants before the interview began, familiarizing them with the research focus and building rapport. We started the interviews by eliciting basic information (e.g., working experience, job responsibilities) to collect background data. In asking key interview questions, we began with easy to answer questions (e.g., participants' understanding of CE and circular product design in supply chains) and moved to more complicated questions (e.g., the major stakeholders for circular product design), following a designed question order. All questions were designed to be open-ended, which allowed the participants to offer additional insights. We designed probes and prompts for each question, which helped to keep the interviews closely relevant to the research focus and allowed for unexpected data to emerge. For example, we listed a group of stakeholders in line with the literature. While we asked a general question and let participants discuss their thinking on any stakeholder impact, we used this list as a prompt to acquire pre-designed specifics if a stakeholder was not mentioned. The interviews were recorded in order to transcribe and analyze textual data. After the interviews, we sent an executive summary to each participant to validate our interpretation of their answers.

Before the data collection, the interview questionnaire and the interview protocol were reviewed by two experienced CE researchers. They confirmed that the interview questions and protocol were appropriate. Based on their feedback, some minor revisions were made to ensure the language and terms used in the interview questions were clear and unlikely to cause misunderstandings.

3.2. Data analysis

We conducted a thematic analysis of the transcribed interview data. Thematic analysis focuses on capturing (or coding) the shared meaning (or codes) around an organized core concept within qualitative data. Emerging codes with conceptual commonality are then conceptualized into a 'theme,' which is an identified pattern across the entire dataset relating to the research questions (Braun & Clarke, 2006; Neuendorf, 2019). The themes represent the major aspects of the findings. Thematic analysis uses an inductive reasoning approach that is structured in a systematic fashion, providing conceptual guidance (Aronson, 1995).

In the coding process, we followed the six-step approach proposed by Braun and Clarke (2006) to perform a rigorous analysis. First, we transcribed each interview recording into textual data. We read and re-read the transcripts to become familiar with the data and developed initial ideas and patterns. Second, we developed codes from the textual data. Each code was developed in relation to a specific aspect that is central to the research questions. In this process, code labels were assigned to portions of the transcribed texts. For example, the attribute of 'standardized packaging,' or 'design for disassembly,' or 'less complex product composition,' or 'product/materials labeling' was continuously found in our dataset. Based on the conceptual commonality, we developed the code, 'modularity and standardization in design,' following the literature (Krikke et al., 2004) and collated all relevant textual data to this code. The emerging codes were further refined and consolidated according to their conceptual aspects. Third, we developed potential themes across the codes, where conceptually correlated codes were collated into one potential theme. For example, two emerging codes, 'modularity and standardization in design' and 'collaboration,' have different operational attributes. However, they were highlighted by participants as necessary moves in implementing circular product design. Therefore, we incorporated them into the theme 'circumventing measures to overcome barriers.' In this analysis, we followed the criteria of 'internal homogeneity' and 'external heterogeneity' (Braun & Clarke, 2006). We required that the data within a theme had conceptual coherence, but those between themes could have distinct natures. Fourth, we reviewed the themes and codes against the research questions through a process of refining, upgrading, downgrading, and deleting. For example, two potential codes in the stakeholder groups, 'direct competitors' and 'industry leaders,' initially emerged from the textual data. However, our analysis showed a high correlation between these two stakeholder groups in the interview data, where the adoption of circular product design by industry-leading companies forces competitors to follow. Therefore, we opted to downgrade 'competitors' and used 'industry leaders' as a salient stakeholder. Fifth, the final themes and codes were defined and named, and their relevance to the research questions was examined. We developed the code, 'industry leaders taking the lead,' clarifying its operational focus under the theme 'stakeholder impact.' Finally, three themes and their associated codes were reported according to the analysis above, as shown in Figure 1.

We followed the literature to determine the sample size required for the interviews. Guest et al. (2006) state that 'data saturation' – where no new information or themes are observed in the textual data – is an important criterion when measuring a sufficient interview sample size. The authors conducted an experimental study and found that saturation occurs within the first 12 interviews for a homogenous group of research participants (Guest et al., 2006). Their study results on sample size were confirmed by Ando et al. (2014). Our data collection also observed that data saturation occurred within the first 12 in-depth interviews. We stopped data collection after conducting three more interviews, which generated no new insights.

4. Results, analysis, and findings

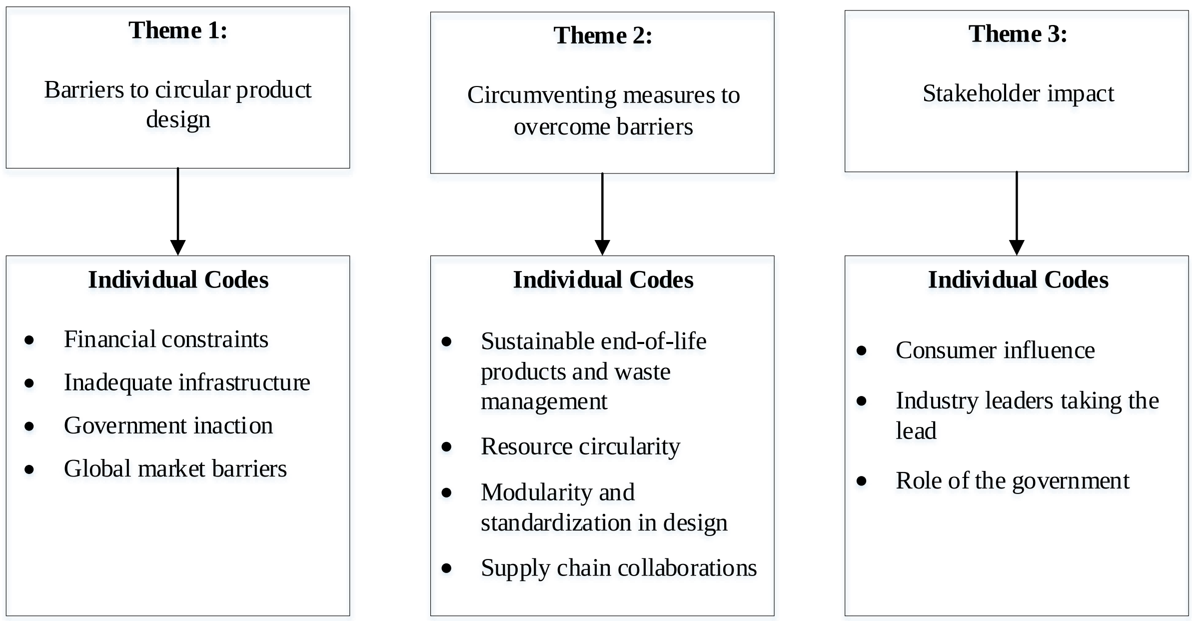

Figure 1 Results of thematic analysis

Figure 1 shows the three themes emerging from the analysis. Each theme contains individual codes that were developed from coding processes to support the theme. *Barriers to circular product design* involve four major barriers to circular product design. *Circumventing measures to overcome barriers* provides a framework of solutions to these barriers. *Stakeholder impact* highlights three salient stakeholder groups that firms need to strategically deal with in their adoption of circular product design: *'the government,'* '*industry leaders,*' and '*consumers.*'

4.1. Barriers to circular product design

Four prominent barriers to circular product design were found: *financial constraints, inadequate infrastructure, government inaction, and global market barriers.* Financial constraints include increasing material costs, low profit margins, and certification and labeling costs. The responses show concerns about increasing material costs and low profit margins. New materials that incorporate reusable, durable, and reliable attributes are required in circular product design, which increases costs. Often, the use of reusable materials decreases the durability of the products. One of our sample firms found that the use of 75% 'recycled polyethylene terephthalate' (rPET) in their plastic bottles diminishes the structural integrity of these bottles. Thus, it is important that firms invest heavily in developing innovative materials for circular product design. One may expect the increased material costs to be offset by cost savings through recovery and recycling. However, our data suggest that most of the sample firms have not achieved cost-efficiency in the mass collection, transportation, disassembly, and reuse of these materials, because the supply chain infrastructure of reverse resource flows is not fully established (we later discuss the details of this barrier in 'inadequate infrastructure'). Therefore, the higher costs of using more sustainable materials are unlikely to be paid off in the near future. Our participants indicated that, in the absence of government funding and favorable taxation, such high material costs create a significant entry barrier, especially for small and medium enterprises (SME). The low profit margin is also an important financial barrier noted in responses. Our participants felt that many SMEs that have invested in circular product design are unlikely to have "a break-even in two years."

Firms that adopt circular product design also face additional certification and labeling costs. New design approaches (e.g., the design for disassembly) and new materials (e.g., compostable substances) used in circular product design may cause changes in product safety and performance standards. Our participants indicated that their companies commonly have to pay for certifications and labeling to meet regulatory requirements or to evidence a satisfactory quality standard. The legal frameworks for circular-design products are different across countries and even local regions. Customers' requests for labeling also vary. Firms also need to invest in re-certifications and maintain the standards. These add more costs to the firms. One participant stated,

> *The government is looking at putting in labeling certification…it will create a barrier if people are going to have to apply for certification. Certifications are expensive. So that is a financial barrier. There is also the process of managing that certification, so it's not just paying for it.*

'Inadequate infrastructure' as a significant barrier emerged from our data. The participants were concerned that supply chain designs and operations are currently not efficient and effective in supporting circular resource flows. Circular product design substantially advances re-engineering processes. However, the current infrastructure for reverse logistics does not fully support the design strategy. Managers were frustrated with the low collection rates of returned products and the few logistics services and facilities designated for recovery. In particular, circular product design technologically increases efficiency in bulky disassembly and recovery and thus speeds up resource circularity. Operationally, however, supply chains are not designed to efficiently manage the increased reverse resource flow, or a 'mass recovery.' One manager from a packaging manufacturing company noted that their customers in the retail industry do not have sufficient capacity to handle a large number of product returns, despite adopting the recyclability concept in their product design. This shows that the success of CE adoption depends on the concurrent development of a circular system at product design, strategic, and operational levels. Moreover, the inadequate infrastructure prevents firms from continuously receiving responses and data needed to review and improve the circular product design. Consumers' concerns with performance/safety and operational efficiency in recovery are unlikely to be quickly addressed and improved. Furthermore, the participants claimed that there is a lack of initiatives in resource circularity beyond immediate supply chains. Currently, the circular product design strategies focus on compatibility and recovery within immediate supply chains. Few industry-wide standard product designs incorporate recoverability across different supply chains. The inadequate infrastructure for trading wastes and by-products across supply chains (e.g., industry symbiosis) discourages design concepts beyond the immediate supply chains.

Interestingly, the collaborations with upstream suppliers in the context of circular product design were not noted by participants as a significant challenge. A potential reason is that suppliers are traditionally required to engage with firms in product design, ensuring the availability of raw materials and component compatibility. Thus, these manufacturing companies can manage their collaborations with upstream suppliers by incrementally adding circular concepts into the current product design. It shows that the major challenges in circular product design from a supply chain perspective are centered on the management of reverse resource flow by the downstream firms. This requires 'horizontal collaborations' of diverse downstream stakeholders (e.g., consumers/customers and government).

Our data show that 'government inaction' is another major barrier to circular product design. Our participants believed the government was currently inactive in the transition towards CE. The government generally allows consumers and industries to take a leading role in developing a market for circular products. At present, society is in transition to a circular model, and traditional linear production and consumption remain dominant. Thus, CE-oriented firms, mostly SMEs, have intense competitive pressure from traditional and large businesses. Given the increased costs in the short run, some of these firms rely on government support for economic viability. However, legislation and policies do not sufficiently motivate the firms' initiatives in resource circularity. In particular, the government focuses on coercive force (e.g., penalties), but a support mechanism is missing. There is a lack of CE-favorable policies, including taxation and grants. Importantly, the New Zealand government does not actively take the lead in establishing supply chain infrastructure for circular resource flows, such as finance mechanisms, material marketplaces, and industry collaborations. The present government CE initiatives do not support these innovative firms in developing competitive advantages, and hence, substantially discourage the incentive to produce a circular product design. One manager from a personal care product manufacturing company stated,

> *In changing from one system to another, there is a significant cost to business and therefore, if they (the government) don't make that workable, then there is no incentive to businesses to change, or there is disincentive even if the intention is there. It's a disincentive to change because of the cost to business. So, they are also very important.*

'Global marker barriers' refer to concerns with inconsistent sustainability policies and regulations across countries. For instance, the certifications for 'circular products' vary across global markets, adding challenges to the product design. The requirements for reusable components and biodegradable materials are significantly different across countries; for example, while products designed to use compostable materials are certified in one country, the composting process may not eventuate at the end of the products' life cycle in another country due to regulatory differences. In other words, initiatives in circular product design are constrained by the different legal frameworks across countries. One participant stated, *"Market barriers. So, if we manufacture in a country that has sustainable legislation and then selling to a country that doesn't, it will be hard to manage the end-of-life of the product."*

Tracy (2010) points out that triangulation is important to improve the credibility of the findings in qualitative research, where the use of multiple data sources, the types of data, and the theoretical frameworks converge on the same conclusions. In this study, we followed Denzin (1978) to conduct 'data triangulation' and 'methodological triangulation' to evaluate the robustness of the findings in our qualitative analysis. First, we used an alternative data source. We collected secondary information from company reports, internet websites, and press reports. We regularly found that the companies to which our interview participants belonged reported challenges in dimensions that were consistent with our qualitative findings. For instance, a company reported that when the firm collaborated with its Brazilian supplier to convert bottles to biobased sugar plastic in 2014, the substantial increase in the cost of raw materials was the biggest obstacle. The initial financial investment in 2014 was reported at nearly NZ $2 million. This validates our finding that increased material costs are a prominent financial barrier to firms that adopt circular product designs.

Second, we collected quantitative data in interviews to evaluate our qualitative interpretations. We requested our participants to quantitatively rank the barriers. The results are reported in Table 3. We used a weighted average to illustrate the ranking scores, where a value range from zero to four was assigned between 'not important' and 'very important,' respectively. *Financial barriers, governmental barriers, infrastructural barriers,* and *global market barriers* were top-ranked barriers. The quantitative rankings are in complete agreement with the qualitative interview data, thus confirming the validity of the thematic analysis results.

Table 3 Ranking of Barriers by Participants in the Interviews

BARRIERS	**Importance to circular product design adoption**					
	Very important (4)	**Important (3)**	**Moderately important (2)**	**Slightly important (1)**	**Not important (0)**	**Weighted average**
Financial Barriers:	12	2	1	0	0	3.7
Technological Barriers:	7	2	4	1	1	2.9
Employee/Staffing Barriers:	5	5	4	1	0	2.9
Governmental Barriers:	9	4	1	1	0	3.4
Society Barriers:	4	5	5	1	0	2.8
Infrastructural Barriers:	10	4	1	0	0	3.6
Global Market Barriers:	5	8	1	0	1	3.1

4.2. Circumventing measures to overcoming barriers

We found four circumventing measures to overcome the barriers to circular product design: '*sustainable end-of-life products and waste management*,' '*resource circularity*,' '*modularity and standardization in design*,' and '*collaboration*.' Modularity and standardization in design refer to products that are configured with interchangeable modules, which allows product components to be easily exchanged and replaced. Modular design increases the product compatibility that supports the life-extension strategies of repair, upgrades, and modifications. It also improves the operational efficiency for disassembly and reuse/remanufacturing/refurbishment at the end of the product life cycle. Moreover, the standardization in product design facilitates mass production, which reduces energy and material consumption. The effectiveness of modular product design in resource circularity can be enhanced by introducing industry-wide standards, for example, in packaging. One manager from a logistics service company noted,

> *We have been working with product design for a very long time, and we have a product that really works well. For me, it's that standardization because it's both easy to*

manage and it's industry good. It's important for industries to have standardized packaging because it allows infrastructure to be developed to process that packaging. So, if companies that operated in the same industry had packaging that was the same material makeup, then it would make it easier to recycle. That would contribute to the movement towards the circular economy.

In our data, supply chain collaborations were found to be an important circumventing measure. Suppliers' adherence to design strategies and concepts is important. It requires early supplier engagement in circular product design, which secures resource flows and suppliers' adherence to the design concepts. Collaborations with customers are also essential. Customers provide important information about what wastes can be used as a resource in circular product design. Modular and standardized design, in particular, requires supply chain collaborations, which provides a reliable and predictable material flow for the design strategy. Such collaboration in product design should be extended beyond the immediate supply chains to incorporate sector-wide attributes. Some of our sample firms collaborated with their competitors by sharing facilities, resources, and infrastructure to bypass the present inefficient CE infrastructure (e.g., reverse logistics), which motives innovative product design. However, collaborations across supply chains were rare in our sample. One issue is there is no mechanism to support cross-sector CE operations. It is difficult for firms to explore resource circularity in a different supply chain that it does not operate. The cross-sector CE operations rely on governments, industry-leading companies, and associations to establish collaborations. Nonetheless, as discussed earlier, government involvement remains low. Industry symbiosis hardly functions at a product design level, partially due to the sensitive business information in design strategies and the competition between competitors.

Our data show that the development of sustainable end-of-life products and waste management is important to circular product design. Producers are required to have systematic thinking and an organized approach, in the form of organizational culture, strategies, and operations, to proactively manage environmental impacts of products at the end of the product life cycle. Such CE thinking at the strategic level provides producers with a favorable operational context to incubate innovative product design strategies. Many firms lack strategic thinking in managing sustainable operations, which prevents the development of circular product design. A textile rental service company in our sample successfully incorporated the cascading process into product design when sustainable operations were being seriously considered as their business strategies. The business manager noted,

I see product design as a very important part of the circular economy because garments can be very difficult to recycle at the end of their life cycle so using natural fibers to

> *produce garments is much better than synthetic fibers. None of our stuff is single-use. Our products are designed to be washed and reused over 500 times. Once a product is retired, we then make it into something else. We turn table cloths into glass wipes, and towels into rags. The third use of our products is what we call ragged out. Uniforms are cut up and sold to painters and mechanics as rags. It's a cascading flow of materials.*

'Resource circularity' is another circumventing measure found in our data. Many of the sample firms found their major difference to traditional business, or their core competitive advantage, was to actively utilize waste as resources and incorporate this concept into their product design strategies. The wastes within immediate supply chains and from other industries can be valuable materials that are used for innovative product design. One recycling service company in our sample innovatively converted waste generated from the building industry to courier satchels for e-commerce. The general manager noted, "*[I]t's kind of a critical part. So not only to be able to utilize resources that are waste. So, designing products that start from waste. But also designing products that can be reused."*

4.3. Stakeholder impact analysis

In this study, we focused on exploring the prominence of stakeholders with salient influences relating to circular product design. We found the three most prominent stakeholders and impacts to be '*consumer influence,' 'industry leaders,' and 'the role of the government.'* These three stakeholder groups are interrelated in their support of firms' successful implementation of circular product design.

Consumers were identified as a prominent stakeholder. All respondents from our sample firms believed product design strategies are driven by consumer demand. However, it is necessary for consumer perception and purchasing patterns to undergo radical change as a result of circular product design. In a traditional linear economy, most of the end-of-life products are sent to landfills. There is no requirement for post-consumption operations. However, under the CE principle, products are designed to include operations at the end of their life cycle in order to establish resource circularity. Nevertheless, it is not guaranteed that consumers will follow the design concept on a continuous basis. One of our sample firms in the recycling service industry designed a recyclable bottle wrapped with a protective sleeve, which needs to be removed for full recycling. However, the manager was concerned that consumers' acceptance of the design requires the removal of the sleeves, which seems somewhat 'inefficient' in a traditional linear model. Moreover, the concepts of remanufacturing/refurbishing/reuse contradict the traditional consumption preference for new products. Consumers' concerns about the quality/performance/safety of recyclable products have not been fully addressed, which also influences firms in implementing circular product design strategies in practice. Consumers are an important financial stakeholder to firms. Their strong stakeholder power, legitimacy, and urgency influence the economic viability of firms. Unless driven by a strong consumer preference for 'circular product and services,' circular product design strategies of firms are unlikely to be successful.

The government is one of the most crucial stakeholders. The participants believed that the top-down approach of CE adoption is an important driving force in circular product design at the firm level. Given the radical changes of CE on the holistic production and consumption model, it requires strong stakeholder power, legitimacy, and urgency to drive various parties in society. Our data show the government is the only stakeholder that can carry such influence. As discussed earlier, firms' design concepts and strategies significantly depend on consumers' perceptions and purchasing patterns. Government regulations, legislations, and education can effectively reshape consumption behavior in favor of circular products and services. Supply chains can also be pulled by market demand and regulations to collaboratively design and produce circular products and services. Government-level standards on remanufactured/refurbished/reused products can considerably increase consumers' confidence in quality/performance/safety. Public procurement is an effective force that supports circular product design. Driven by high bargaining power and purchasing volume, public procurement can increase the demand for circular products and services along supply chains, driving innovation. A manager from a personal care product manufacturing industry noted,

> *The government has an incredibly important role to play, but the type of role that they play is different to companies. So, they are very important, but it should be through incentives, through support, through making it possible to make those changes and make those changes fast.*

The last prominent stakeholder group that was found in our data is industry leaders. Industry leaders are commonly the focal firms in the supply chains, and thus have relatively high stakeholder power. Strategic use of their power can lead to supply chain integration, enabling circular product design, such as modular and standardization design. Also, an industry symbiosis that synopsizes CE initiatives and design strategies across different supply chains is more likely to be established through the support of industry leaders. As leading companies in the industries, these firms have relatively high stakeholder legitimacy to lobby governments to establish industry-wide CE product standards, regulations, and grant mechanisms. As shown in our sample data, most firms that have adopted circular product design are SMEs, which rely on the design concept as an innovative business strategy. They expect the industry-wide CE initiatives introduced by industry leaders to strengthen their market positions, and the design collaborations with industry leaders to develop competitive advantages. One respondent stated, *One big industry can channel many medium industries and so many small industries. If they take one step towards the circular economy, then everything down the line will change. That is why I am saying that industry leaders are important.*

Our data show that managers believe that industry leaders are more likely to strategically and systematically drive positive CE transitions in production, thus providing an institutional motive and pressure to adopt circular product design in supply chains.

In order to explore circular product design from diverse perspectives, we also collected our interview data from a sample of academics. It is interesting to analyze their opinion in contrast to those of the practitioners in our sample. The data show qualitatively similar results between academics and practitioners, while we found a relatively different propensity in terms of stakeholder impact. Academics largely focus on 'production-driven' circular product design. Practitioners, however, are more likely to rely on 'consumption-driven' circular product design strategies. Consumers were highly ranked and extensively discussed as the top stakeholder class by our sample practitioners. They expected strong market demand for circular products and services that can grow their competitive advantages by adopting circular product designs. From an academic perspective, industry leaders are highly regarded among the three stakeholder groups. Academics are more likely to focus on proactive changes in industries, evidenced by the potential of improving operational and environmental performance (e.g., secure supply chain resource flows and waste reduction). In our sample, both academics and practitioners agreed that the government is an influential stakeholder that firms need to deal with in their adoption of circular product design.

The difference in the propensity demonstrates a different stakeholder perspective relating to circular product design. Managers focus on profitability. Thus, their design strategies are highly driven by the needs of consumers/customers, who are an important financial stakeholder in businesses. From an academic perspective, a broad vision of stakeholders (e.g., the natural system and industry development) is represented in the data. Hence, a vigorous industry-driven change in product design is expected. This shows that the different stakeholder perspectives create a gap between social desirability and business practices for CE and circular product design. The gap is more likely to be bridged by governments, as found in our data. Governments have a higher degree of stakeholder power, legitimacy, and urgency than businesses and consumers. Governments are more likely to systematically measure the economic and environmental impact from a multiple-stakeholder perspective. The interplay of government, industry leaders, and consumers as three prominent stakeholder groups found in our study is more likely to support the successful adoption of circular product design.

We followed the literature and included various stakeholder groups (e.g., media, NGOs, industry associations) in the data collection and analysis. However, the results do not show that they are in the top stakeholder class. Following the descriptive stakeholder theory, the findings show that firms need to prominently and strategically deal with governments, consumers, and industry leaders to overcome circular product design barriers.

We applied the same data triangulation and methodological triangulation approaches to validate our findings on stakeholder impact from the interview data. We collected secondary information from company reports, internet websites, and press reports. We found that the companies represented by our interview participants frequently reported their search for support and collaborations with the government and industry partners, and their successful practices in educating and motivating environment-conscious consumers (e.g., building a nationwide collection system). These secondary data confirm our qualitative interpretation of major stakeholder impacts. For example, a company reported its successful launch of New Zealand's first ‘high-density closed loop packaging return program.’ It relied heavily on government support in the forms of grants, educating and motivating environment-conscious consumers, and building a nationwide collection system.

Furthermore, we requested our participants to quantitatively rank the stakeholder classes as they did when ranking the barriers. The results are reported in Table 4. *Government*, *industry leaders*, and *consumers* were top-ranked stakeholders, which affirms the validity of the thematic analysis findings.

Table 4 Interviewees’ Ranking of Stakeholder Classes

Stakeholders	**Importance to circular product design adoption**					
	Very Important	**Important**	**Moderately important**	**Slightly important**	**Not important**	**Weighted average**
Government	9	2	3	0	1	3.2
Media	1	9	1	3	1	2.4
Industry Leaders	11	1	2	0	1	3.4
Competitors	7	4	3	0	1	3.1
Suppliers	7	3	4	1	0	3.1
Consumers	10	4	1	0	0	3.6
NGOs	3	2	5	5	0	2.2
Pressure Groups	3	4	4	3	1	2.3

Community	7	4	3	1	0	3.1
Educational Institutions	6	4	3	0	2	2.8

5. Summary and discussions

This study explored the barriers to circular product design and the circumventing measures from a stakeholder perspective. Using a sample of 15 interviews with industry and academic experts on circular product design, we found four major barriers: '*financial constraints,' 'inadequate infrastructure,' 'government inaction,'* and *'global market barriers.'* The circumventing measures we identified are *sustainable end-of-life products and waste management, resource circularity, modularity and standardization in design,* and *supply chain collaboration*. Three prominent stakeholders that are significant for firms' management of the barriers and circumventing measures are, *'governments,' 'consumers,'* and *'industry leaders.'*

5.1. Academic contributions

Our findings provide important academic contributions. We extended the supply chain management literature of CE studies by exploring adoptions at the product design level. Previous studies have mainly focused on a strategic level and found diverse business strategies in the transition to CE (e.g., Genovese et al., 2017; Govindan et al., 2015). Our study from a circular product design perspective supports the operationalization of these business strategies. The resource circularity at the end of the product life cycle is grounded on the upgrades of the product concept and resource allocation at the product design phase. Our findings of barriers, circumventing measures, and stakeholder impacts provide knowledge to guide firms to upgrade their product design strategies in line with CE.

Our findings from a circular product design perspective complement the literature on the barriers to CE adoption. At the strategic level, a wide range of barriers has been identified in the literature (see Table 1). In contrast, the barriers at the product design level are mainly associated with financial, infrastructure, policy, and market aspects. The intercorrelations of the barriers from both strategic and design perspectives provide insight into improving operational efficiency in the adoption of CE by firms in the supply chains. For instance, firms can strongly improve the supply chain infrastructure in circular resource flow (e.g., capacity for mass recovery), which will support both circular product design (e.g., modular design for bulky disassembly) and business strategies (e.g., planning and control system for remanufacturing).

The global market barrier emerged as a new discovery from the product design perspective, reflecting inconsistent regulations and policies in different countries/regions that hinder firms' global operations in circular resource flows. The global market barrier has not been reported in the CE literature at the strategic level. Circular product design substantially changes a product's nature. The uncertainty over the performance/safety/quality of 'new products' requires a collaborative product design framework, where firms' innovative design strategies can be assured by government regulations and standards. Our findings show the need for integration between the 'top-down' and 'bottom-up' approaches in CE adoption, with collaborative circular product design providing such an opportunity. Moreover, our findings indicate that CE research should incorporate the complexity of global supply chain operations in the circular model. The difference in regulations and infrastructure, and uneven development of the circular system across countries, is a significant obstacle. In particular, as our sample country of New Zealand shows, innovative companies rely heavily on their overseas supply chain partners in resource circularity. Our study shows a clear avenue for developing CE research in the global supply chain context.

From the stakeholder perspective, our findings on the impact of consumers and the government on circular product design are consistent with those found at the strategic level (as in Table 1). However, we further explored their position as the top stakeholder class when identifying the barriers to circular product design. Our findings show that firms need to primarily and strategically manage stakeholder relationships with consumers and governments. Interestingly, we found that the stakeholder impact of 'industry leader' is salient from the product design perspective, in contrast to the literature that focuses on the strategic level. A potential reason is that circular product design is a radical innovation in production models. Firms have concerns with the associated business risks and potential competitive disadvantages, and thus rely on industry-wide changes. Because of the strong stakeholder impact, industry-leading companies are more capable of driving such radical innovation at the industry level. Our findings infer that wider stakeholder support is required in managing the radical change of circular product design.

Our findings on circumventing measures show the interdependence of circular product design and business strategies in CE adoptions. The circumventing measures found in this study from a circular product design perspective are significantly linked with the concurrent development of CE business strategies. We found that modularity is a design-specific circumventing measure. However, it relies on strategic supply chain collaborations to create resource circularity, including suppliers' early engagement and adherence to the design strategies and concepts. Also, industry-wide standardization is more likely to maximize the efficiency and effectiveness of modular design in resource circularity, which requires collaborations across different supply chains to explore product modules. Our study highlights the importance of developing the capacity of firms at both product design and strategic levels, which mutually support the successful transition to CE.

Our study provides important theoretical contributions. First, our study extends the value of stakeholder theory, especially its descriptive aspect, by exploring a supportive stakeholder class in the proactive adoption of business practices by firms. The descriptive stakeholder theory has been widely adopted in the literature to study the implementation of new business practices, especially sustainable supply chain management (Seles et al., 2016; Villena & Dhanorkar, 2020). These studies have focused on the nature of coercive stakeholder force in adoptions of business practices. Specifically, customer firms have higher stakeholder power over upstream suppliers than other stakeholders (e.g., consumers and governments). Thus, customer firms can more effectively pressure suppliers to adopt sustainable operations. In contrast, we focused on the nature of supportive stakeholder force in the proactive adoption of circular product design by firms. Our findings provide evidence that firms can strategically and deliberately search for and categorize the top stakeholder class that provides the most significant support. While all stakeholders can be potentially supportive, cost-efficiencies and strategic breakthroughs are more likely to be gained by primarily dealing with stakeholders in the top supportive class. Our study adds understanding to the descriptive stakeholder theory by revealing the innovative use of stakeholder classification in supporting the voluntary adoption of business practices.

Second, in previous studies on the barriers to supply chain implementations of CE practices, scholars that employed stakeholder theory mainly focused on the instrumental aspect to explore various stakeholder perspectives (Govindan & Hasanagic, 2018). In contrast, our theoretical contribution to this theoretical framework is our application of its descriptive aspect in the supply chain adoption of CE. We extended previous studies by finding a prominent class across various stakeholders. Firms are required to deal with all instrumental stakeholders in their CE adoption. Our findings highlight that, in adopting a circular product design as the first initiative in a firm's transition to CE, firms can strategically select and manage relationships with a group of stakeholders found in a high stakeholder class. This can substantially improve operational efficiency in implementing a circular product design and incrementally overcome the identified barriers for successful adoption.

5.2. Practical implications and a roadmap for circular product design

Based on the study results and findings, Figure 2 proposes a roadmap for circular product design that encompasses the critical drivers and supporting conditions at multiple levels (i.e., macro, meso, and micro levels). To overcome barriers to circular product design, collaborative efforts are required from all the stakeholders involved. At the macro level, governments can enact legislation and use economic incentives to create a business environment that is supportive to circular product design. Governments need to work with communities to provide infrastructures that are essential for recovering value from end-of-life products and wastes, for example, waste collection and recycling facilities. Furthermore, they need to partner with educational institutions on environmental education to transform the culture to be more receptive to circular products. At the meso level, establishing industrial symbiosis, which is often realized in eco-industrial parks, helps facilitate the waste-to-resource exchanges among partnering firms. At the micro level, firms should develop circular product design capabilities and reconfigure their supply chains (e.g., reverse logistics and localization) to enable a circular flow of products and materials. They can lobby governmental support and educate consumers on the environmental benefits of their circular products. The following two subsections discuss the relevant managerial and policy implications in detail.

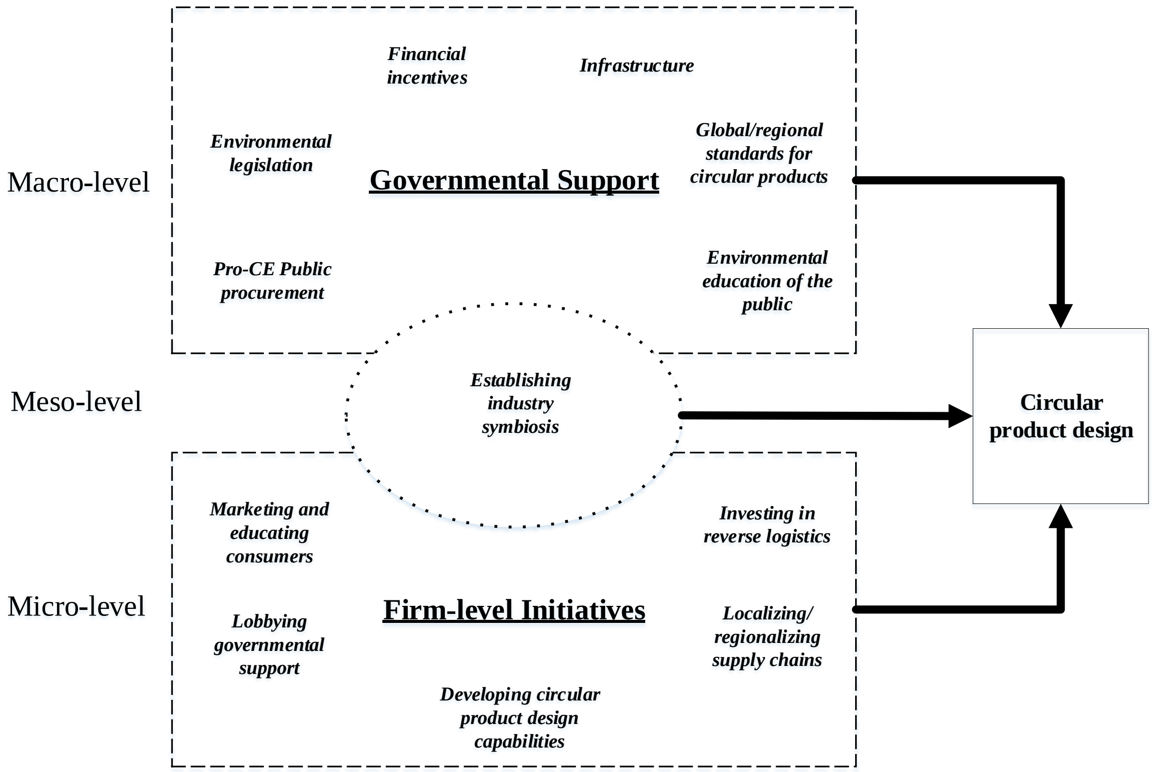

Figure 2. A roadmap for circular product design

5.2.1. Managerial implications

Given the significance of the global market barrier to circular product design, firms may localize/regionalize their supply chains, providing design strategies with a consistent legal and operational framework. Supply chain operations can be localized within the regions of Australasia, North America, Asia, or Europe. Similar regulation and policy systems around 'point of production' and 'point of sale' support the development of innovative design strategies and their implementations in supply chains. Also, localization reduces the supply chain complexity and length. Firms are more likely to have a high level of supply chain visibility and thus effective management of resource circularity in the supply chains. A pragmatic approach must be taken in localizing supply chains, as supply chains are globalized to leverage a cost-effective supply of resources, labor, production, and transport. As part of building resilience against Covid-19, many managers are prepared to redesign their supply chains, including localized productions. This would provide an opportunity to integrate circular product design into the supply chain design.

As highlighted in this study, reverse logistics is a critical factor in supporting the implementation of circular product design. Firms need to strategically invest in establishing efficient and effective reverse logistics in supply chains, supporting the rapid development of competitive advantages by resource circularity. The investment may focus on exploring innovative collaborations with third-party logistics service providers, given their mediating position in the supply chains.

Our finding of significant consumer impact on circular product design shows that firms need to strategically market circular products/services and educate consumers. Consumers often misperceive the performance, quality, and safety of circular products (e.g., remanufactured products), and confuse them with ‘second-hand’ products (Hazen et al., 2017). Firms need to provide consumers with clear specifications and warranties for remanufactured products, which should be as-new or ‘better than new’ in quality. Meanwhile, many working examples (e.g., car components) could be provided to educate consumers and increase their confidence in circular products. Manufacturers can collaborate with downstream firms (e.g., retailers) to effectively promote products at the point of sale. Also, cost savings from purchasing circular products should be clarified to consumers. Consumer acceptance is likely to improve if the economic and environmental benefits of buying circular products are highlighted.

Firms can lobby governments to provide financial and technological support, which can substantially reduce the costs of circular product design, and in turn, make the low-cost benefit to consumers appealing. Many countries/regions have embraced CE (e.g., China, the United Kingdom, Japan, the European Union), and many more countries are likely to follow. The rapid governmental movement toward CE provides businesses with an opportunity to proactively showcase their circular attributes and disclose financial and technological needs. This will help expedite the establishment of more favorable legislation, tax incentives, and other sponsors. As a result, firms will be more likely to achieve cost-efficiency through effective governmental support, which can be further used to promote the low-cost benefit of circular products to consumers and trigger demand.

Apart from developing circular product design capabilities, firms should lobby governments to establish industry standards for circular product design and the extension of standards to a global context. This would significantly assure consumers of the as-new quality, performance, and safety of circular products. As found by our study, industry leaders are a strong stakeholder that can lead supply chain/industry collaborations in government lobbying and the operationalization of the aforementioned practices. Industry leaders can effectively incorporate these practices into business strategies. Given their prominent profile in industries, industry leaders that take action can develop reputational assets and innovatively strengthen their market-leading positions. Moreover, an industry leader that acts as the ‘first mover’ can quickly become a standard-setting firm, securing a long-term leading position in industries and contributing to operational and financial performance.

5.2.2. Policy implications

Governments play an instrumental role in facilitating and incentivizing circular product design for the transition to CE. In the short to medium term, governments need to provide or improve infrastructure to make it more feasible and efficient to reuse/recycle materials in society (Govindan & Hasanagic, 2018). Their inaction may disincentivize the efforts of sustainable businesses, while proactive actions may help to improve the competitiveness of circular products in the market. Governments have significant powers and means to encourage positive behavioral changes. For example, they can enact tougher environmental legislation and provide tax incentives and subsidies for producing and selling circular products (Farooque, Zhang & Liu, 2019). They may consider a drastic increase in charges for businesses that send waste to landfills and use the raised revenue to subsidize waste management and value recovery operations. It is a challenging task, but the national/regional governments also bear the responsibility to work with governments in other countries/regions to establish global/regional standards for overcoming the global market barriers to circular product design.

Public procurement is a vehicle that can drive the development of circular product design by businesses. Governments should incorporate resource circularity criteria into their procurement programs when selecting suppliers and awarding tenders (Alhola et al., 2019). The substantial purchasing volume and government buying power can provide economic incentives and drive innovative product design. Businesses that adopt circular product design are more likely to develop their competitive advantages through pro-CE public procurement. Public procurement of circular products and services should also coincide with a clear marketing and education campaign to increase consumers’ acceptance of circular product design. In turn, the increasing market demand would attract more businesses to adopt the design concept and strategy.

We found that governments have a significant stakeholder impact on circular product design, especially in establishing cross-sector collaboration and industry symbiosis (e.g., eco-industrial parks). Collaborations across different supply chains are a critical factor in enhancing resource circularity; however, these are challenging due to the limited supply chain scope of individual firms. Our findings indicate that governments are in the best position to facilitate the establishment of new buyer-supplier relationships beyond the immediate supply chains of firms. Governments are more likely to have an overview of demands and supplies for wastes and by-products across sectors. Their significant stakeholder impact on industries indicates that firms are more likely to build trust and collaborations with untraditional supply chain partners under governmental support and supervision. Moreover, governments can utilize their strong stakeholder impact to create standards for labeling and the practices of circular product design. Such standards can be extended to a global context through international collaborations between governments. Government-endorsed industry collaborations are more likely to increase businesses' confidence in the investment.

In the long term, governments need to foster an environmental culture as the journey to CE is likely to be a marathon. A culture of environmental protection must be deeply embedded in the lives of citizens to make a circular economy a reality. Recent studies on the circular food supply chain (Farooque, Zhang & Liu, 2019) and smart waste management (Zhang et al., 2019) in China have advocated for the improvement of environmental education as a key measure to overcoming barriers to CE by transforming the culture. The same policy measure is expected to be necessary for other countries as well. Governments should improve environmental education in communities and a wide range of educational institutions, including schools, polytechnics, and universities. Curriculums on the topics of sustainability and CE need to be strengthened. The world is becoming increasingly aware of the need for a transition to CE, and through education, consumers are more likely to embrace more sustainable consumption behaviors and favor circular products. Such a change will create a virtuous cycle in the industry whereby businesses will be required to realign their product design principles with customer preferences.

6. Conclusion

This study focused on circular product design in the development of CE and circular supply chain management. In the literature, there has been little research on CE adoptions from the product design perspective or a focus on prominent stakeholder classes. In line with these research gaps, we explored the major barriers to circular product design and the circumventing measures from a stakeholder perspective. Our study complements the CE literature by providing novel insights into product design strategies, which also supports the development of CE adoption at the strategic level (e.g., innovative business models).

This research makes several original contributions. First, it is believed to be the very first study to examine barriers to circular product design and the circumventing measures. It is also the first to employ a stakeholder perspective to systematically investigate and prioritize stakeholder impact in driving the transition to circular product design. This topic warrants further studies, given that circular product design is the foundational step to CE. Second, this study generates new knowledge on barriers to CE at a product design level. In contrast to the wide range of barriers to CE and circular supply chain management at a strategic level, barriers to circular product design are mainly related to financial, infrastructure, policy, and market aspects. In addition, this study discovered global market barriers to be an area that has not been reported in the literature. Third, the theoretical contributions of this study are underlined by its extension of the value of stakeholder theory, especially its descriptive aspect, to the context of the supply chain adoption of CE from a circular product design perspective. Finally, the study findings have important practical implications, and a roadmap for circular product design is proposed. We highlight the complexities of circular product design in global supply chain operations, and the importance of governmental functions in facilitating effective collaborations within and across supply chains/industries.

Despite its original contributions, this study has its limitations. We had a relatively small sample size of 15 participants from New Zealand with industry and academic expertise in circular product design. The circular product design concept is still nascent; therefore, it was challenging to recruit further participants who had sufficient knowledge of circular product design. It should be noted that not many New Zealand businesses have adopted circular product design, although the country has a strong culture of environmental protection. In this study, we focused on the practical experience and expert opinion of practitioners and academics, which allowed us to derive novel insights on circular product design. Future research may focus on selected aspects of this research (e.g., the relationship between modular design and resource circularity), where a larger sample is likely to be generated. Once circular product design becomes more widespread in the industry, a large-scale survey or secondary-data research could be used to understand its overall performance implications. Also, future research could study the relevant concepts in a different national context and compare the results. Previous research has widely studied CE in China (Su et al., 2013; Zhang et al., 2019; Zhang, Venkatesh et al., 2021), whereas product design strategies have not been broadly explored. There are different production and consumption models between developing and developed countries (Mangla et al., 2018). The findings based on a Chinese sample could provide an interesting comparative analysis with those from our New Zealand context. The European Union and the United Kingdom have been actively implementing the CE concept in the past decade. It would be interesting to investigate their progress in circular product design and the effectiveness of their government policy measures.

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Appendix: Interview questions

What stakeholders do you consider to be the most influential in guiding organizations towards circular product design? And how?

How do the following stakeholders impact the adoption of circular product design in supply chains?

What is the role of each in the adoption of circular product design in supply chains? Please rank their importance to circular product design adoption.

- National/ Regional Government & Regulations/ Regulatory Bodies
- Media
- Industry Associations
- Industry Leaders
- Competitors
- Customers (local, foreign)
- Suppliers
- Consumers
- NGOs
- Pressure Groups (Environmental activists)
- Community
- Educational Institutions
- Business Consultants

What barriers do organizations face when adopting circular product design? You may refer to the list provided, but we hope you can identify more barriers that are not on the list.

- Lack of circular product design expertise/knowledge
- Lack of market demand for circular products

- Lack of pressure from customers/consumers
- The high cost of materials required in circular products
- The circularity of materials is not practiced for product end-of-life
- Lack of reverse logistics and supply chain processes to circulate materials
- Consumers and customers do not practice reuse/recycle of materials
- The public has little awareness and knowledge of the importance of circular product design
- Lack of traceability where the products go
- Many products are sold overseas, so it is not realistic to loop the materials back

Please rank the following categories of barriers in terms of importance to circular product design adoption:

- Financial barriers
- Technological barriers
- Employee/Staffing barriers
- Governmental barriers
- Society barriers
- Infrastructural barriers
- Global market barriers