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Product platforms as enablers for the circular economy in construction: an integrative review☆

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ABSTRACT

This integrative review evaluates the potential of product platforms to support the circular economy in construction. Circular economy aims to minimize waste by promoting the regeneration of materials and products. Product platforms appear to support the circular economy because they facilitate efficiency by leveraging repetitions, standardization, and modularization providing potential to increase resource efficiency and reuse. These overlapping definitions lead to the assumption of promising interceptions between product platforms and circular economy that could prove valuable in transitioning away from the traditional 'take-make-waste' paradigm. This transition is especially needed in construction. Despite its success in other industries, such as manufacturing, aerospace and defense, product platforms remain largely unexplored in the construction sector. This review sets out to firstly, review barriers to circular economy in construction; secondly, establish a terminology by providing an overview of how product platforms are defined and applied in construction, and thirdly, investigate the benefits of product platforms that could address barriers to circular economy in construction. To do so, this study integrates two strings of research: The barriers to circular economy and the potential of product platforms in construction. By reviewing literature on both areas, this study outlines that product platforms in construction share technical, process, and knowledge domains, while standardization, modularization and configuration are relevant precursors to their application. Further, this study identifies four enablers through which product platform benefits could address barriers to circular economy: commercialization, reuse, derisking, and innovation. Ultimately, this integrative review provides avenues for further research, insights for policymakers, researchers, and industry practitioners interested in promoting the circular economy through platforms.

1. Introduction

Rising global constraints on resource consumption accelerate pressures to transition to circular economy (CE) decoupling environmental impacts from economic growth (Castro et al., 2022; Kjaer et al., 2019). CE is a "a regenerative economic system which necessitates a paradigm shift to replace the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials throughout the value chain, to promote value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations. It is enabled by an alliance of stakeholders (industry, consumers, policymakers, academia) and their technological innovations and capabilities" (Kirchherr et al., 2023, p. 194).

Construction accounts for approximately 50 % of material-use (European Commission, 2020) and creates around 100 billion tons of waste worldwide. The sector consumes roughly 38 % of global energy and emits 37 % of energy-related greenhouse gases (UNEP, 2022). Linear construction practices are unsustainable, with impacts predicted to worsen as the growing population requires housing (UN, 2022; UNEP, 2022). CE can support sustainable construction by enabling economic activity while constraining environmental impacts (Acerbi et al., 2022; Acerbi & Taisch, 2020).

Construction's project orientation and high customisation complicate disassembly, recovery, and remanufacturing of components (Bressanelli et al., 2019; Taddei et al., 2022) and results in supply chain

Abbreviations: CE, Circular Economy; ICT, Information and Communications Technology.

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fragmentation appearing vertically (lack of knowledge exchange across phases), horizontally (lack of communication within phases), and longitudinally (project teams dissolve, knowledge is lost) (Hall et al., 2018; Jones et al., 2022). Construction thus is stuck in re-innovating solutions across stakeholders and projects (Davies & Brady, 2000). Literature outlines the need to reduce this fragmentation but has not implemented solutions (Acerbi & Taisch, 2020; Bressanelli et al., 2019). Levers to achieve CE include rethinking designs, supply chain integration, and implementation across building phases (Bressanelli et al., 2022; Kirchherr et al., 2023).

Scholars have identified platform thinking as a systemic approach to foster CE (Thuesen et al., 2022; Kedir et al., 2023). "Platform thinking is the process of identifying and exploiting the shared logic and structure in a firm's activities and offerings to achieve leveraged growth and variety" (Sawhney, 1998, p. 1). Research refers to platforms either as markets (marketplaces, e.g. Airbnb) or technological platforms (Product Platforms) (Gawer, 2014). This study will focus on the latter as a collection of components, processes, knowledge, and partnerships shared by multiple products or services (Robertson & Ulrich, 1998). Product Platforms divide a system into stable core and variable periphery (core-periphery model), enabling standardization, modularization, and repetition of components, processes, knowledge, and partnerships while allowing customization (Harlou, 2006; Robertson & Ulrich, 1998). Standardization provides scalability, repetition, and efficiency, while the variable periphery enables customization (Meyer & Lehnerd, 1997). In other words, product platforms allow "highly differentiated products to be delivered to the market without consuming excessive resources" (Robertson & Ulrich, 1998, p. 20).

Product platforms can manifest within firms, supply chains, and industry ecosystems, with openness increasing respectively as more stakeholders co-create the product platform. These stakeholders are referred to as complementors. The higher the degree of openness, the higher the number of complementors and the higher the extensiveness with which specifications are shared (Aksenova & Oti-Sarpong, 2024; Gawer, 2014; Nambisan & Sawhney, 2011). While research has typically argued that product platforms are driven by one firm and are based on closed or semi-open interfaces (Aksenova & Oti-Sarpong, 2024), recent research increasingly moves away from the duality between open and closed (Hall et al., 2020; Jones et al., 2022; Cao et al., 2021). Accordingly, product platforms can be initiated, facilitated, and maintained by an orchestrating entity (Hall et al., 2020; Zhou et al., submitted for publication), e.g., an organization, network of organizations, industry, or regulatory body. The orchestrator controls shared interfaces to ensure interoperability as complementors meet the product platform's requirements (Mosca et al., 2020; Hall et al., 2020; Boudreau, 2017). Depending on the interfaces' openness, product platforms can be applied to a vertically integrated company controlling the entire supply chain or to a loosely coupled system of companies that co-create a product platform under the platform orchestrator's facilitation. We adopt the definition of a supply chain platform according to Gawer's (2014) conceptualization of technological platforms as a continuum along three manifestations (West, 2007) (Table 1).

This study acknowledges the possibility of supply chain interaction (Gawer, 2014), enabling collaboration in developing and maintaining product platforms. Communication across phases and projects, e.g., between designers and demolishers, can ensure that a standardized component, module or entire building can be kept at the highest circulation through design-for-X (e.g. manufacturing, variety, adaptability, refurbishment, deconstruction, disassembly). As complementors can standardize according to interface specifications, a "domino effect of standardization" is triggered. The standardization of components, processes, knowledge, and partnerships across the supply chain subsequently creates benefits for orchestrators and complementors, as interoperability within supply chains and potentially within the industry increases.

Table 1
Classification of technological platforms (Gawer, 2014).

	Internal Platform	**Supply-Chain Platform**	Industry Platform
Level of Analysis	Firm	Supply chain	Industry Ecosystem
Interfaces	Closed	Selectively Open	Open Interfaces
Coordination Mechanisms	Managerial Hierarchy	Contractual Relations	Ecosystem Governance
Technological Architecture	Modular Design & Core-Periphery	Modular Design & Core-Periphery	Modular Design & Core-Periphery

Although previous scholars state that product platforms were "more or less unknown in the project-based construction industry" (Thuesen & Hvam, 2011, p. 340), product platforms address fragmentation under project orientation (Fergusson & Teicholz, 1996; Hall et al., 2020). Research has seen a significant increase in product platform adoption, in particular under the concept of industrialized construction, which emphasizes standardization, modularization, automation, and prefabrication to streamline, cut costs, increase quality and efficiency (Hall et al., 2020; Jones et al., 2022; Cao et al., 2021). However, research on product platforms typically does not address sustainability strategies, such as CE (Thuesen et al., 2022). This is likely a missed opportunity, as the benefits of product platforms, including reduced fragmentation, documentation, learning, and efficiency, could address barriers to CE in construction. We propose that product platforms can act as a systemic management approach for CE and decarbonization in construction by optimizing resource flows and valorizing resources within and across supply chains as well as construction phases (Bressanelli, Visintin, & Saccani, 2022; Saccani et al., 2023). A review of the literature is needed to synthesize barriers to CE and the application of product platforms in construction to ultimately answer the following research question:

How could Product Platforms act as enablers to overcome barriers to Circular Economy in construction?

Section 2 outlines the methodology. Section 3 presents CE barriers before elaborating on product platforms in construction. Subsequently, Section 4 integrates both areas and elicits how product platforms can address CE barriers. Section 5 discusses theoretical implications and future research avenues. Section 6 concludes and outlines limitations.

2. Methodology

This article follows the integrative review methodology, aiming to take stock of dynamic topics that receive heightened research interest but have not been comprehensively reviewed (Torraco, 2016). As CE has a high priority, especially in construction, this article aims to offer new perspectives through the combination with product platforms. Readers can expect a synthesis of CE barriers and product platforms benefits in construction, and an introduction of future research avenues (Snyder, 2019; Whittemore & Knafl, 2005).

2.1. Planning

Having defined the study's objective, we mapped the literature on both topics (Fig. 1) following two literature strings: (1) CE barriers in construction and (2) product platforms in construction. A preliminary literature scan confirmed that only two studys investigate the intersection of both topics (Thuesen et al., 2022; Kedir et al., 2023).

2.2. Execution

Scopus was screened using keywords derived from the research question. The search was limited to articles published in English until 31.12.2024. We ran two search strings: (1) "circular economy" AND "construction" OR "building" and (2) "product platform" AND "construction" OR "building". The subject areas were limited to environmental sciences, engineering, social studies, material science, computer

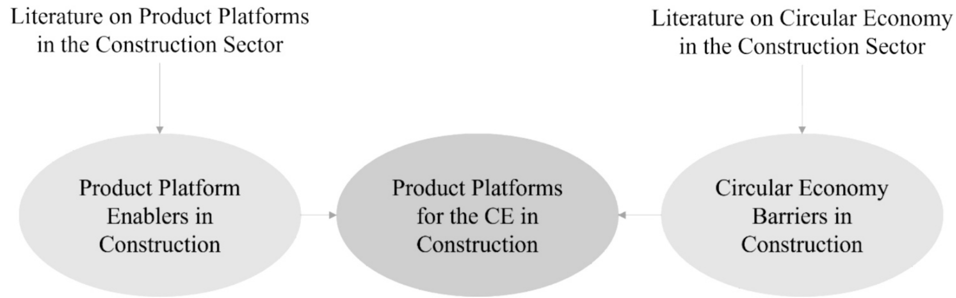

Fig. 1. Integrative Review Design.

science, business, earth science, and decision science. Search string 1 was applied to abstracts and targeted review papers, as CE in construction has been reviewed extensively. Search string 2 applied to title, abstract, keywords, included full and conference papers, as product platforms are not extensively researched in construction. To balance results, we complemented search string 2 with 27 additional papers from WebofScience using the same criteria and removing duplicates. Titles and abstracts were screened, followed by full-text assessments for inclusion based on set criteria:

Search String 1: Papers investigating the barriers to circular economy in construction.

Search String 2: Papers applying product platforms to the construction sector.

Two reviewers conducted the screening process (Fig. 2). Discrepancies were resolved through discussion.

2.3. Reporting

Data was extracted by coding using Atlas.ti. For search string 1, focused on barriers to CE in construction, we used codes for barriers and related terms (challenges and inhibitors). Search string 2 papers were coded according to recurring topics and patterns based on iterative reading (Appendix A) to map existing research on product platforms in construction. Two authors reviewed the content and organized It into themes for reporting.

3. Analysis

3.1. Circular Economy Barriers in Construction

Circular buildings should embrace lifecycle thinking to reduce resource needs (Chen et al., 2022; Gamage et al., 2024; Benachio et al., 2020) throughout all lifecycle phases and across environmental, technological, societal, governmental, economic, and behavioral dimensions (Pomponi & Moncaster, 2017). Despite growing efforts, CE in construction is in its infancy. Based on the reviewed literature, we identified

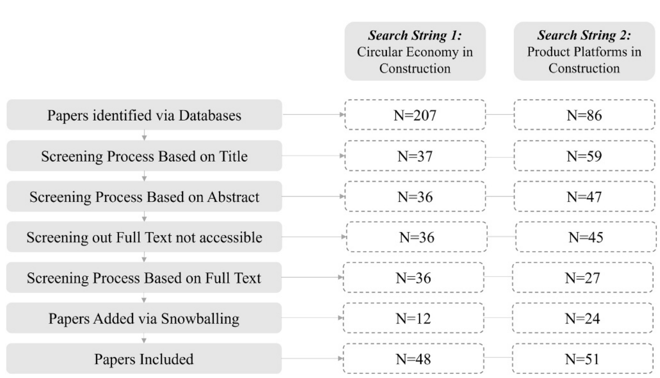

Fig. 2. Screening Process.

8 categories of CE barriers hindering CE implementation (Table 2). We mapped these barriers to the building phases: design, construction, operation/maintenance, and end-of-life (Akhimien, Latif, & Hou, 2021; Benachio, Freitas, & Tavares, 2020; Chen et al., 2022).

3.1.1. Cultural Barriers

The exploration of CE is hindered by "reluctance and risk aversion" (Wuni, 2022, p. 6; Charef, Morel, & Rakhshan, 2021), exacerbated by hesitant company cultures and change resistance. Low margins create profitability pressure, lowering risk readiness for change and innovation (Illankoon & Vithanage, 2023; Wuni, 2022). The lack of awareness and CE benefits increase change resistance (Hossain, Ng, Antwi-Afari, & Amor, 2020; Huang et al., 2018; Xue et al., 2021; Munaro et al., 2020). In designs, virgin materials are preferred to secondary materials (Oluleye et al., 2022; Osei-Tutu, Ayarkwa, Osei-Asibey, Nani, & Afful, 2023; Oluleye et al., 2022; Osei-Tutu, Ayarkwa, Osei-Asibey, Nani, & Afful, 2023; Sajid et al., 2024), as reuse is perceived as costly and risky (Anastasiades et al., 2021; Mata et al., 2021; Rakhshan et al., 2020). Culturally, linear thinking is dominating the industry (Charef, Morel, & Rakhshan, 2021; Kazmi & Chakraborty, 2023; Sharma, Kalbar, & Salman, 2022), underlining the need to embrace systems thinking throughout building phases (Kazmi & Chakraborty, 2023).

3.1.2. Market Barriers

The lack of demand for reused materials results in immature secondary markets and limited supply thereof (Oluleye et al., 2022; Çimen, 2021; Oluleye et al., 2022; Illankoon & Vithanage, 2023; Yu, Yazan, Junjan, & Iacob, 2022). To create a market and drive scale, demand uncertainties for reused materials, components, and products need addressing by increased data availability and exchange (Hossain, Ng, Antwi-Afari, & Amor, 2020; Ipsen et al., 2021; Sajid et al., 2024). Fragmentation prevents information exchange, preventing market creation and lowering reuse rates (Gorgolewski et al., 2008; Rameezdeen et al., 2016; Rose & Stegemann, 2018; Sajid et al., 2024). Additionally, relevant technologies, tools, and procedures are not sufficiently developed to ensure competitiveness and commercialization of reused resources (Charef, Morel, & Rakhshan, 2021; Huang et al., 2018; Osei-Tutu, Ayarkwa, Osei-Asibey, Nani, & Afful, 2023).

3.1.3. Financial Barriers

Consequently, CE comes at a price premium, diminishing its competitiveness further (Osei-Tutu, Ayarkwa, Osei-Asibey, Nani, & Afful, 2023; Ruiz et al., 2020; Wuni, 2022). As business models are lacking, funding remains insufficient to address the abovementioned hen-and-egg-problem (Hossain, Ng, Antwi-Afari, & Amor, 2020; Sajid et al., 2024). CE requires systemic change, and new technologies are often incompatible with existing processes, equipment, and practices (Mata et al., 2021), leading to high upfront investments (Ipsen et al., 2021; Oluleye et al., 2022; Wuni, 2022; Oluleye et al., 2022; Ipsen et al., 2021). Ownership models focus on short-term profits, preventing the potential of CE to generate long-term savings, maximize gains through long-term partnerships, prolong buildings' lives, and valorize resources

Table 2
Results Search String 1 (“Circular Economy” AND “construction” OR “building”).

Barrier Category	Phase(s)	References
Cultural	**All**	Anastasiades et al., 2021; Charef, Morel, & Rakhshan, 2021; Hossain et al. (2020); Huang et al., 2018; Illankoon & Vithanage, 2023; Mata et al., 2021; Kazmi & Chakraborty, 2023; Munaro et al., 2020; Oluleye et al., 2022 Osei-Tutu et al. (2023); Rakhshan et al., 2020; Sajid et al., 2024; Sharma, Kalbar, & Salman, 2022; Wuni, 2022; Xue et al., 2021
Uncertainty & Risk	All	
Hesitant Culture	All	
Profit Pressure	All	
Lack of Awareness	All	
Linear Thinking	All	
Preference for Virgin Materials	Design, Operation/ Maintenance	
Market	**Design, End-of-Life**	Charef, Morel, & Rakhshan, 2021; Çimen (2021); Hossain, Ng, Antwi-Afari, & Amor, 2020; Huang et al., 2018; Illankoon & Vithanage, 2023; Ipsen et al., 2021; Köhler et al. (2022); Oluleye et al., 2022; Oluleye et al., 2022; Osei-Tutu et al. (2023); Roxas et al., 2023; Sajid et al., 2024; Wuni, 2022; Yu, Yazan, Junjan, & Iacob, 2022
Lack of Demand & Supply	Design, End-of-Life	
Lack of Scale	Design, End-of-Life	
	Design, End-of-Life	Anastasiades et al., 2021; Charef, Morel, & Rakhshan, 2021; Çimen (2021); Gaustad et al., 2018; Gorgolewski et al., 2008; Illankoon & Vithanage, 2023; Köhler et al., 2024; Mata et al., 2021; Eberhardt et al., 2019; Ipsen et al., 2021; Minunno et al., 2018; Oluleye et al., 2022; Osei-Tutu et al. (2023); Roxas et al. (2023); Ruiz et al., 2020; Sajid et al., 2024; Wuni, 2022; Zhang, Ming, & Bao, 2022
Low Competitiveness	Design, End-of-Life	
Lack of Funding & Business Case	Design, End-of-Life	
Lack of Incentives	Design, End-of-Life	
High Cost	Design, End-of-Life	
Long-Term Profits of CE	Design	
Cost for Reverse Logistics	Design, End-of-Life	
Knowledge	**All**	Adams et al., 2017; Charef, Morel, & Rakhshan, 2021; Hossain, Ng, Antwi-Afari, & Amor, 2020; Ipsen et al., 2021; Kazmi & Chakraborty, 2023; Kirchherr et al. (2017); Köhler et al., 2024; Mata et al., 2021; Eberhardt et al., 2019; Munaro et al., 2020; Oluleye et al., 2022; Osei-Tutu et al. (2023); Rakhshan et al., 2020; Ruiz et al., 2020; Senaratne et al., 2023; Sajid et al., 2024; Urbinati, Chiaroni, & Chiesa (2017); Wuni (2022)
Lack of Practical Knowledge	All	
Lack of Data	All	
Lack of Professional Skills	Design, End-of-Life	
Lack of Systems, Guidelines, Standards	All	
Lack of Shared Understanding	All	
Management & Organizational	**All**	Charef, Morel, & Rakhshan, 2021; Eberhardt et al., 2019; Hossain, Ng, Antwi-Afari, & Amor, 2020; Huang et al., 2018; Köhler et al., 2024; Kazmi & Chakraborty, 2023; Oluleye et al., 2022; Oluleye et al., 2022; Osei-Tutu et al. (2023); Pomponi & Moncaster, 2017; Wuni, 2022; Yu, Yazan, Junjan, & Iacob, 2022
Lack of Management Support	All	
Additional Admin. & Legal Requirements	Design, End-of-Life	
Unsupportive Warranty Structures	Design, End-of-Life	
Future Uncertainty	Design	
Lack of CE Indicators	Design, End-of-Life	
Regulatory	**All**	Bhavsar et al., 2023; Charef, Morel, & Rakhshan, 2021; Çimen (2021); Ghisellini et al., 2018; Hossain, Ng, Antwi-Afari, & Amor, 2020; Illankoon & Vithanage, 2023; Köhler et al., 2024; Mata et al., 2021; Ipsen et al., 2021; Oluleye et al., 2022; Oluleye et al., 2022; Osei-Tutu et al. (2023); Rakhshan et al., 2020; Ruiz et al., 2020; Wuni, 2022; Xue et al., 2021; Yu, Yazan, Junjan, & Iacob, 2022
Lack of Policies, Standards	All	
Lack of Infrastructure	End-of-Life	
Lack of strict Penalties & Strong Incentives	Design, End-of-Life	
Inflexibility hinders Innovation	All	
Technological & Technical	**Design, End-of-Life**	Anastasiades et al., 2021; Ghisellini et al., 2018; Hossain, Ng, Antwi-Afari, & Amor, 2020; Huang et al., 2018; Illankoon & Vithanage, 2023;
Immaturity of Technology	Design, End-of-Life	

Table 2 (*continued*)

Barrier Category	Phase(s)	References
Lack of Innovativeness	Design, End-of-Life	Köhler et al., 2024; Charef, Morel, & Rakhshan, 2021; Chen et al., 2022; Ipsen et al., 2021; Oluleye et al., 2022; Osei-Tutu, Ayarkwa, Osei-Asibey, Nani, & Afful, 2023; Oluleye et al., 2022; Rakhshan et al., 2020; Roxas et al., 2023; Sajid et al., 2024; Wuni, 2022; Xue et al., 2021; Yu, Yazan, Junjan, & Iacob, 2022; Zhang et al., 2022
Complexity of Deconstruction	End-of-Life	
Lack of Enabling Digital Technologies	Design, End-of-Life	
Supply chain	**All**	Charef, Morel, & Rakhshan, 2021; Chen et al., 2022; Gorgolewski et al., 2008; Hossain, Ng, Antwi-Afari, & Amor, 2020; Köhler et al., 2024; Ipsen et al., 2021; Munaro et al., 2020; Oluleye et al., 2022; Osei-Tutu et al. (2023); Rakhshan et al., 2020; Rameezdeen et al., 2016; Rose & Stegemann, 2018; Sajid et al., 2024; Sharma, Kalbar, & Salman, 2022; Wijewickrama, Rameezdeen, & Chileshe, 2021; Wuni, 2022; Xue et al., 2021
Fragmentation	All	
Lack of Information Flow	All	
Insufficient Collaboration	All	
Involvement of Additional Players	All	
Complex Reverse Logistics	End-of-Life	
Lack of Understanding of New Rules	All	
Lack of Support & Involvement	All	

(Eberhardt et al., 2019). Low prices of virgin materials decrease CE’s economic attractiveness and restrict funding availability (Mata et al., 2021; Ipsen et al., 2021). Additional complexities and cost lie in design and reverse logistics, including additional transportation, reprocessing, and storage (Anastasiades et al., 2021; Çimen, 2021; Gaustad et al., 2018; Illankoon & Vithanage, 2023). The need to purchase expert knowledge and software adds financial disadvantages (Ipsen et al., 2021; Osei-Tutu, Ayarkwa, Osei-Asibey, Nani, & Afful, 2023). These barriers complicate business cases of reselling reused materials, components, and products (Zhang et al., 2022; Osei-Tutu et al., 2023; Roxas et al., 2023; Charef, Morel, & Rakhshan, 2021).

3.1.4. *Knowledge Barriers*

The missing shared understanding of CE results in misinterpretations (Adams et al., 2017; Eberhardt et al., 2019; Kirchherr et al., 2017; Urbinati, Chiaroni, & Chiesa, 2017), while the industry lacks demonstration projects and documented best practices to benchmark and build implementation knowledge (Hossain, Ng, Antwi-Afari, & Amor, 2020; Mata et al., 2021; Munaro et al., 2020). The lack of professional skills, specifically for collaboration across phases and projects (Rakhshan et al., 2020; Senaratne et al., 2023; Ipsen et al., 2021), signals a need for learning (Mata et al., 2021; Wuni, 2022). The design and end-of-life phase require significant skill developments, as buildings need to be designed-for-x (e.g. deconstruction, disassembly, adaptability) (Osei-Tutu et al., 2023; Charef, Morel, & Rakhshan, 2021; Munaro et al., 2020). These phases lack support by knowledge management systems (Oluleye et al., 2022; Charef, Morel, & Rakhshan, 2021), guidelines and standards (Ruiz et al., 2020; Sajid et al., 2024), data transparency by e.g. using Building Information Modelling (BIM) (Wuni, 2022; Xue et al, 2021), material passports, and communication methods to improve collaboration (Charef, Morel, & Rakhshan, 2021; Hossain, Ng, Antwi-Afari, & Amor, 2020).

3.1.5. *Management & Organizational Barriers*

Additional barriers arise due to additional communication, legal, and administrative requirements that come with CE within a work culture that is unsupportive of change. “The need to reinvent project delivery practices, reconfigure supply chains, alter entrenched industry practices, and establish new working relationships” (Wuni, 2022, p. 19) hinder companies from completing projects fastest and most economically (Charef, Morel, & Rakhshan, 2021). Stakeholders optimize material choice, design, and construction according to short warranty periods, which are “misaligned with long-term goals of CE” (Eberhardt et al., 2019) and accentuate potential performance risks of reused materials. Functional changes during constructions' long lifecycles and future material reuse induce uncertainty into the management of circular construction (Pomponi & Moncaster, 2017). Without proven results, management is more likely to defer to traditional processes (Oluleye et al., 2022; Kazmi & Chakraborty, 2023; Yu, Yazan, Junjan, & Iacob, 2022). Industries need comprehensive indicator frameworks for CE evaluation (Oluleye et al., 2022; Huang et al., 2018) to demonstrate value and stimulate change (Charef, Morel, & Rakhshan, 2021; Hossain, Ng, Antwi-Afari, & Amor, 2020).

3.1.6. Regulatory Barriers

Regulatory barriers include the lack of legislation, policies, standards, and codes to support and incentivize the transition (Mata et al., 2021; Rakhshan et al., 2020; Bhavsar et al., 2023; Çimen, 2021). Adequate incentives to guide the industry (Gaustad et al., 2018; Oluleye et al., 2022) and appropriate infrastructure for reverse logistics are missing (Illankoon & Vithanage, 2023; Oluleye et al., 2022; Oluleye et al., 2022), while regulations frequently contradict CE (Ipsen et al., 2021). Penalties for illegal dumping and legislative support for effective resource management are insufficient (Oluleye et al., 2022; Ipsen et al., 2021). Codes and standards often solely apply to virgin materials, favoring the latter (Ruiz et al., 2020). These circumstances lower credibility and adoption of secondary materials (Ghisellini et al., 2018; Hossain, Ng, Antwi-Afari, & Amor, 2020). Finally, regulations' inflexibility prevents innovation, a core necessity in this transition (Oluleye et al., 2022; Charef, Morel, & Rakhshan, 2021).

3.1.7. Technological & Technical Barriers

Increased technical complexity arises from additional requirements for design, deconstruction, and reverse logistics, including transportation, reprocessing, and storage (Köhler et al., 2024; Rakhshan et al., 2020; Osei-Tutu et al., 2023). This complexity cannot be managed with existing knowledge, resources, or processes (Charef, Morel, & Rakhshan, 2021; Wuni, 2022). Current recycling technologies are immature, and research to improve them is insufficient (Hossain, Ng, Antwi-Afari, & Amor, 2020; Illankoon & Vithanage, 2023; Ipsen et al., 2021). The lack of proven technologies, such as take-back systems, and limitations in tracking secondary materials increase complexities (Huang et al., 2018; Oluleye et al., 2022; Sajid et al., 2024). Technological advancements require innovation and change management, which is prevented by cultural, regulatory, and financial barriers. Technology to design-for-x and digital technology need implementation to enable supply chain integration, data transparency, and resource efficiency (Ghisellini et al., 2018; Xue et al., 2021; Yu, Yazan, Junjan, & Iacob, 2022).

3.1.8. Supply Chain Barriers

Fragmentation is characterized by a lack of information flow and collaboration along the supply chain (Chen et al., 2022; Ipsen et al., 2021; Munaro et al., 2020; Sharma, Kalbar, & Salman, 2022). "The lack of information hinder[s] the introduction of practices and awareness of circular thinking" (Munaro et al., 2020) and can "cause a considerable amount of rework and wastes" (Chen et al., 2022). This stems from the supply chains' linearity and the lack of collaboration with additional players, e.g., demolishers or reprocessors (ibid; Oluleye et al., 2022). However, there is a lack of support from stakeholders due to a missing understanding of new roles, effective communication, and collaboration (Osei-Tutu et al., 2023; Sajid et al., 2024). Missing infrastructure to sort, refine, and store recovered materials and knowledge of disassembling and redirecting materials for reuse contribute to poor adoption (Charef, Morel, & Rakhshan, 2021; Oluleye et al., 2022).

3.2. Product Platforms in Construction

Having explored CE barriers in construction, the following section outlines the results of search string 2, delineating how product platforms are defined in construction (Table 3).

3.2.1. Standardization, Modularization & Configuration

Product platforms combine commonality with distinctiveness and vary in degrees of predefinition (Jansson, Johnsson, & Engström, 2013; Yazdi, Fini, & Forsythe, 2020). They rely on standardization, modularization, and scalability (Baldwin & Clark, 2000; Hvam, Mortensen, & Riis, 2008; Meyer & Lehnerd, 1997). While standardization drives scale economies and efficiency by reducing complexity (Baldwin & Clark, 1997; Jansson et al., 2019; Simpson, 2004; Han, 2009), modularization enables customization (Banihashemi, Tabadkani, & Hosseini, 2018; Yazdi, Fini, & Forsythe, 2020; Lennartsson et al., 2023).

Modules are subsystems "designed for reuse" (Harlou, 2006, p. 43), i.e. components, non-volumetric or volumetric systems (Peltokorpi et al., 2018). A modularization strategy defines actors, tasks, responsibilities, processes, and components over the building's lifecycle (Peltokorpi et al., 2018) and manages "complexity by breaking up a complex system into discrete components, which interact through standardized interfaces within a standardized architecture, one can eliminate what would otherwise be an unmanageable spaghetti tangle of systemic interconnections" (Gawer, 2014, p. 1242). As modular components inform modular processes and supply chains (Fine, 1998, 2000; Voordijk et al., 2006), product platforms induce modularity in components, processes, knowledge, and partnerships (André et al., 2019; Baldwin & Clark, 1997; Peltokorpi, Olivieri, Granja, & Seppänen, 2018; Robertson & Ulrich, 1998).

Configuration describes "sequential decision-making" (Cao et al., 2021, p.6), which simplifies designs as products are customized by combining pre-defined modules according to project constraints (Erixon, 1998; Wikberg et al., 2014). Three aspects characterize configurators: reusability of parts, embeddedness of expert knowledge, and off-the-shelf technologies enabling automation (Cao et al., 2021; Bourke, 2000). Configurators reduce errors and costs through shorter lead times, increased coordination, and improved documentation, enabling knowledge reuse across projects (Cao & Hall, 2019; Jensen, Olofsson, & Johnsson, 2012; Johnsson & Meiling, 2009).

3.2.2. Technical, Process, and Knowledge dDmains

Based on the reviewed literature, product platforms in construction contain a technical domain (physical components), process domain (supports the delivery of the product) (André et al., 2019; Lennartsson et al., 2023; Eriksson & Emilsson, 2019; Jensen et al., 2013; Lessing, 2006), and a knowledge domain (ensures alignment within and across projects) (Miller, 2001; Jones et al., 2022; Sanchez & Mahoney, 1996; Sanchez, 2005).

(1) Technical Domain

The technical domain describes the physical structure, including "a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched for a building project" (Berglund-Brown et al., 2022, p. 4). Interfaces link modules, and standards govern design rules (Baldwin & Clark, 2000). This domain is the foundation for configurators to "assemble a set of components from a wide range of alternatives to meet the end users' needs" (Cao et al., 2021, p. 2). Harlou (2006) modeled product assortments using a product family master plan, giving insights into product variety, the depth of standardization, impact of customer decisions, and component reuse across product families (product variants generated from a shared set of modules) (Hvam et al., 2008). Harlou (2006)'s part view overlaps with the idea of the technical domain as a "component library" (Piroozfar et al., 2019, p. 10), including standard components stored to be reused across construction projects (Eriksson & Emilsson, 2019; Lennartsson & Elgh, 2018; Simpson, 2004).

(2) Process Domain

Table 3
Results Search String 2 ("product platform" AND "construction" AND "building").

Topic	Description	References
Standardization, Modularization & Configuration (3.2.1)	Standardization is described as the underlying principle of modularization, while both are precursors for configuration. Configuration is based on standardized modules and can vary in the degree of automation, depending on the degree of software integration (e.g., parametric modeling).	Banihashemi et al. (2018); Cao, Bucher, Hall, & Lessing, 2021; Cao & Hall, 2019; Eriksson & Emilsson, 2019; Erixon et al. (1996); Gosling et al. (2016); Han (2009); Jensen et al. (2012); Jensen et al. (2013); Larsson et al. (2016); Levandowski et al. (2015); Malmgren, Jensen, & Olofsson, 2011; Peltokorpi, Olivieri, Granja, & Seppänen, 2018; Piroozfar, Farr, Hvam, Robinson, & Shafiee, 2019; Thajudeen, Lennartsson, Elgh, & Persson, 2020; Voordijk, Meijboom, & de Haan, 2006; Wikberg, Olofsson, & Ekholm, 2014; Winch, 2003; Yazdi, Fini, & Forsythe, 2020; Smiding, Gerth, & Jensen, 2016
Technical Domain (3.2.2)	The technical domain supports the delivery of the construction and acts as a foundation for configuration. It entails specifications about the building's physical assets. These include modularized components, interfaces that link these components and design rules.	André et al., 2019; Berglund-Brown et al. (2022); Cao et al. (2021); Elgh and Johansson (2019); Elgh et al., 2018; Eriksson & Emilsson, 2019; Halman et al. (2008); Jensen et al. (2013);Jones et al. (2022); Kedir et al., 2023; Lennartsson & Elgh, 2018; Lennartsson et al. (2023); Maxwell & Aitchison (2017); Aksenova & Oti-Sarpong, 2024; Thajudeen, Elgh, & Lennartsson, 2022; Thuesen & Hvam, 2011; Veenstra, Halman, & Voordijk, 2006; Voordijk, Meijboom, & de Haan, 2006; Yazdi, Fini, & Forsythe, 2020; Thajudeen, Lennartsson, & Elgh, 2018
Process Domain (3.2.2)	The process domain entails explicit and implicit processes for the construction, assembly, and maintenance of the building. Product modularity as represented in the technical domain translates into process modularity in the process domain.	André et al., 2019; Berglund-Brown et al. (2022); Chai et al. (2012); Elgh and Johansson (2019); Elgh et al., 2018; Eriksson & Emilsson, 2019; Halman, Voordijk, & Reymen, 2008; Jensen et al., 2013; Jones et al. (2022); Kedir et al., 2023; Lennartsson & Elgh, 2018; Lennartsson et al. (2023); Popovic & Rösiö, 2019; Thajudeen, Elgh, & Lennartsson, 2022; Thajudeen, Lennartsson, Elgh, & Persson, 2020; Thuesen & Hvam, 2011; Voordijk, Meijboom, & de Haan, 2006; Yazdi, Fini, & Forsythe, 2020; Zhou, 2024; Thajudeen, Lennartsson, & Elgh, 2018
Knowledge Domain (3.2.2)	The knowledge domain can be integrated into technical and process domains or be a separate entity. It follows the main goal to document, store, maintain, and share knowledge across stakeholders and projects. In this way, knowledge is reused and iteratively accumulated. Knowledge-Based Engineering is frequently discussed as a tool that focuses on the reuse of product and process engineering knowledge.	André et al., 2019; Berglund-Brown et al. (2022); Cao et al. (2021); Chai et al. (2012); Elgh and Johansson (2019); Elgh et al., 2018; Eriksson & Emilsson, 2019; Jansson et al. (2013); Jansson et al. (2019); Jensen et al. (2013); Jones et al. (2022); Kedir et al., 2023; Lennartsson & Elgh, 2018; Lennartsson et al. (2023); Maxwell & Aitchison (2017); Popovic & Rösiö, 2019; Styhre & Gluch, 2010; Thajudeen, Elgh, & Lennartsson, 2022; Thajudeen, Lennartsson, Elgh, & Persson, 2020; Thuesen & Hvam, 2011; Verhagen, Bermell-Garcia, Van Dijk, & Curran, 2012; Zhou, 2024; Thajudeen, Lennartsson, & Elgh, 2018; Thuesen and Hvam, 2009

Product modularity translates into process modularity, as "the execution of building projects must be supported by continuous development processes in which platforms for both technical solutions and processes are developed" (Lessing, 2015, p. 51). This includes processes that indirectly and directly support product realization, e.g., raw material treatment, machining, and assembly operations (Jiao et al., 2007). These processes cater to the chosen customer decoupling point: The later this point, the higher the commonalities and the repetition of processes (Hvam et al., 2008; Zhou, 2024). With each project, knowledge is fed back into the technical domain (Lennartsson et al., 2023), informing the process domain on the adaptation of processes (Jansson et al., 2013; Kedir et al., 2023) (Fig. 3).

The process domain is where design, planning, manufacturing, and assembly are aligned with the product architecture (Peltokorpi et al., 2018; Wikberg et al., 2014, Larsson et al., 2016), while integrating "design and production processes together with the supply chain" (Lessing, 2015, p. 48). This domain aligns with Robertson & Ulrich's

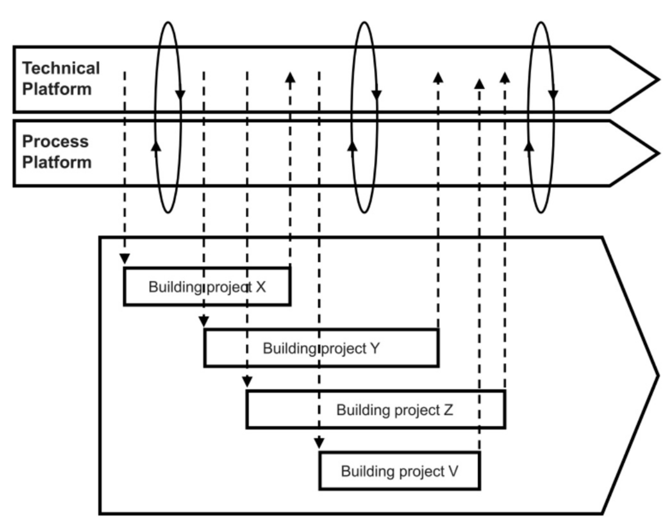

Fig. 3. Technical and Process Domain (Lessing, 2015).

(1998) shareable 'process' asset, with Harlou's (2006) manufacturing or engineering view, which outline the building's instantiation, and with what Malmgren et al. (2011) term assembly view to accommodate onsite processes.

(3) Knowledge Domain

Literature refers to knowledge and information flow as key aspects of product platforms. Knowledge-based-engineering emphasizes the storage and reuse of knowledge to achieve greater efficiencies within and across projects (Elgh et al., 2018; Verhagen et al., 2012; Elgh & Johansson, 2019; Thajudeen, Elgh, & Lennartsson, 2022) and aims "to reduce time and cost of product development, which is primarily achieved through automation of repetitive design tasks while capturing, retaining and re-using design knowledge" (Verhagen et al., 2012, p. 1). Knowledge documentation on best practices, specifications, and design solutions targets fragmentation and enables reuse across projects (Elgh et al., 2018; Larsson et al., 2016). The knowledge domain can represent a separate entity, e.g. a virtual platform (Jansson et al., 2013), a "product library" (Zhou, 2024, p. 3), a "digital warehouse" (Jones et al., 2022, p. 8), or be integrated in the technical and process domain (Eriksson & Emilsson, 2019; Lessing, 2006), just like configurators are carriers of knowledge (Jensen et al., 2013). BIM is often used as a vehicle for knowledge, as it can be used "as a shared language among supply chain participants to be able to consider their parameters, variables, constraints, and objectives simultaneously" (Yazdi, Fini, & Forsythe, 2020). This documentation enables collaboration across the supply chain, phases, projects, and organizations (Elgh & Johansson, 2019; Köhler, Sönnichsen, & Beske-Jansen, 2022; Sudusinghe & Seuring, 2022).

Standardizing project teams across projects additionally increases the ability to reuse and complement knowledge with each project, addressing longitudinal fragmentation (Lessing, 2006; Jones et al., 2022). Standardized agreements across supply chains and predictability in technical and process specifications enable long-term, strategic partnerships, representing the fourth shareable asset: partnerships (Robertson and Ulrich, 1998; Köhler et al., 2024).

The domains need consideration in conjunction, as decisions in one impact the others (Gudlaugsson et al, 2016; Peltokorpi et al., 2018; Popovic & Rösiö, 2019). "It is when the product architecture is combined with a process and knowledge architecture that the phenomenon of an architecture makes sense" (Harlou, 2006, p. 56; Sanchez and Mahoney, 1996). Only synchronized product and process solutions "enable the concurrent fulfillment of the required variety in offerings and economies of scale" (Popovic et al., 2022, p. 3). Based on the abovementioned, we can synthesize the following product platform benefits (Table 4).

4. Product Platform Benefits address Circular Economy Barriers

Having explored the barriers to CE (3.1) and benefits of product platform in construction (3.2), the following section will integrate both theoretically. The overview of CE barriers and product platform benefits (Table 5) visualizes theoretical overlaps. Since addressing individual links between both areas would have fallen short in illustrating the systemic dynamics, we synthesized the links into four enablers to CE in construction: Commercialization (=C), Reuse (=R), Derisking (=D), and Innovation (=I).

The example of a standardized hotel room module will guide the analysis. Please note that one example will not be sufficient to exemplify all dynamics described theoretically. The module is the product platform's physical component and is produced off-site and assembled on-site to build a hotel with similar room modules. The developer orchestrates the module's design and fabrication in collaboration with the supply chain, ensuring that the module's specifications are acceptable to all stakeholders. The mechanical, electrical, and plumbing systems have been synced with the architectural and structural design, and

Table 4
Product Platform Benefits based on Reviewed Literature in Search String 2.

Product Platform Benefits	Description	References
Documentation & Information Flow	Through standardization, technical and processual documentation, knowledge is carried across projects and stakeholders. Consequently, relevant information flows between stakeholders increase. In particular, the knowledge domain ensures significant information is documented, stored, and made available. Through increased documentation, product platforms bridge the three-fold fragmentation, reduce decision deferral, misunderstandings, conflicts, and errors across the supply chain. Standardization and modularization are reflected in a continuous and stable supply chain, which improves information flow.	Berglund-Brown et al. (2022); Cao & Hall, 2019; Eisenreich, Füller, Stuchtey, & Gimenez-Jimenez, 2022; Elgh and Johansson (2019); Elgh et al. (2018); Elmualim et al. (2018); Eriksson & Emilsson (2019); Fine (1998 & 2000); Harlou (2006); Jansson et al. (2013); Jensen et al. (2012); Jensen et al. (2013); Johnsson & Meiling (2009) Jones et al. (2022); Kedir & Hall, 2021; Kedir & Hall, 2021; Kedir et al. (2023); Larsson et al. (2016); Lessing (2006); Lessing (2015); Malmgren et al. (2011); Meyer & Lehnerd (1997); Peltokorpi et al. (2018); Piroozfar et al. (2019); Robertson & Ulrich (1998); Thajudeen, Elgh, & Lennartsson (2022); Thajudeen, Lennartsson, Elgh, & Persson (2020); Thuesen & Hvam (2011); Voordijk, Meijboom, & de Haan (2006); Wikberg, Olofsson, & Ekholm (2014); Yazdi, Fini, & Forsythe (2020); Thuesen et al. (2022); Zhou (2024)
Repetition & Learning	Best practices, specifications and design solutions are stored and repeated across products, projects and stakeholders. As solutions are developed, tested, applied, repeated, and improved, capabilities are built through learning and documentation.	Cao & Hall, 2019; Elgh et al., 2018; Gibb, 2001; Jensen, Olofsson, & Johnsson, 2012; Robertson & Ulrich, 1998; Thajudeen, Elgh, & Lennartsson, 2022; Thuesen & Hvam, 2011; Verhagen, Bermell-Garcia, Van Dijk, & Curran, 2012; Lessing, 2015; Thuesen et al., 2022; Baldwin and Woodard (2009)
Efficiency	The repeated application of standard components, processes, knowledge and partnerships increases efficiency. The higher the degree of standardization, the lower the room for errors and increase efficiency in the material yield. product platforms streamline the development process and reduce development time. The core-periphery model reduces the complexity, by offering a solution space while constraining possible design combinations.	Arashpour et al. (2017); Baldwin & Clark (1997); Banihashemi et al. (2018); Bourke, 2000; Cao, Bucher, Hall, & Lessing, 2021; Cao & Hall, 2019; Bonev, 2015; Elgh and Johansson (2019); Elgh et al., 2018; Erixon, von Yxkull, & Arnström, 1996; Jansson, Mukkavaara, Elgh, & Lennartsson, 2019; Jensen, Olofsson, & Johnsson, 2012; Levandowski, Jiao, & Johannesson, 2015; Meyer & Lehnerd, 1997; Thajudeen, Elgh, & Lennartsson, 2022; Thajudeen, Lennartsson, Elgh, & Persson, 2020; Verhagen, Bermell-Garcia, Van Dijk, & Curran, 2012; Winch, 2003; Erixon, 1998; Harlou, 2006; Jensen et al., 2013

(continued on next page)

Table 4 (*continued*)

Product Platform Benefits	Description	References
Economies of Scale & Reduction of Costs	The repeated use of standardized components, processes, knowledge, and partnerships increases reapplication, efficiency, and scale economies. Efficiency and scale economies translate into lower running costs. Based on the standardized core, firms can derive products at an incremental cost. Flexibility decreases redesign costs incurred by future changes.	Aksenova & Oti-Sarpong, 2024; Baldwin & Clark, 1997; Cao & Hall, 2019; Jansson, Mukkavaara, Elgh, & Lennartsson, 2019; Jensen, Olofsson, & Johnsson, 2012; Meyer & Lehnerd, 1997; Popovic, Schauerte, & Elgh, 2022; Robertson & Ulrich, 1998; Han, 2009; Salvador et al. (2009); Simpson (2004); Thuesen & Hvam (2011); Verhagen, Bermell-Garcia, Van Dijk, & Curran (2012); Voordijk, Meijboom, & de Haan (2006); Winch (2003); Yazdi, Fini, & Forsythe (2020)
Adaptability	Modularization facilitates maintenance, upgrades, add-ons, adaptation, refurbishment, and reuse. Interface reversibility ensures that modules are interchangeable. Configuration simplifies design processes by integrating pre-defined modules. Design-for-x strategies, such as design-for-deconstruction, design-for-manufacturing and assembly, design-for-variety, yield high efficiency in assembly, maintenance, and repair.	Baldwin & Clark (1997); Banihashemi et al. (2018); Cao et al. (2021); Ericsson & Erixon (1999); Erixon (1998); Fixson (2005); Fixson (2005); Gosling et al. (2016); Halman et al. (2008); Jones et al. (2022); Aksenova & Oti-Sarpong (2024); Martin & Ishii (2002); Meyer & Lehnerd (1997); Mhatre et al. (2021); Peltokorpi, Olivieri, Granja, & Seppänen (2018); Voordijk, Meijboom, & de Haan (2006); Winch (2003); Yazdi, Fini, & Forsythe (2020); Smiding, Gerth, & Jensen (2016)

contractors have mapped a process to connect this module to neighboring modules in a way that does not compromise the design intent. These technical and process details are documented in the product platform as the specifications and are made accessible to complementors of the platform.

4.1. Commercialization

As orchestrators and complementors standardize components, processes, knowledge, and partnerships, scale economies can be enabled, as "the expensive nature of secondary materials would lead to a lack of demand which would affect the market for secondary materials" (Oluleye et al., 2022). High prices due to a lack of scale are central market barriers to CE, hindering competitiveness in the marketplace. With product platforms, core components can be applied across several projects; thus, they can be produced at greater scales, leading to higher efficiency and lower costs. These scale effects impact the process domain, where tasks and responsibilities are distributed and repeated across projects. The higher the standardization in partnerships, the more frequent processes are repeated by the same people, supporting specialization and efficiency achieved through learning effects.

Learning and efficiency can be substantiated by knowledge documentation and sharing across phases, addressing the fragmentation and lack of information flow, central supply chain, and knowledge barriers to CE. Increased documentation under product platform application can alleviate management barriers, like rising administrative, legal, and reporting requirements. Lower fragmentation, increased information flow, and data availability can support supply chain efficiency and create synergies with the implementation of digital technology supportive of CE implementation, like material passports or BIM. The latter necessitate but also drive further integration across phases and stakeholders along the supply chain (Anastasiades et al., 2021; Xue et al., 2021; Yu, Yazan, Junjan, & Iacob, 2022).

Ranges of configurators are typically constrained, increasing the predictability of construction projects and preventing deferred decision making, miscommunications, and errors, which currently hinder the efficient use of valuable resources. Tested, validated, and documented solutions can be reapplied and recombined across the supply chain. Predefinition, standardization, and modularization create more reliable costs: As predefinition increases, project specifics decrease and so do complexity and the likelihood of extreme cost, both of which currently disincentivize the conduct of circular construction. Complexity particularly challenges reverse logistics and deconstruction. We see the potential of product platforms to not only lower the complexity of buildings' designs but also the handling at the building's end-of-life, enabling further scale economies and increased efficiency, addressing market and financial barriers currently "making resource recovery economically unattractive" (Tennakoon, Rameezdeen, & Chileshe, 2022).

Together with scale economies and efficiency, the costs of circular construction could decrease. As components are standardized, product platforms ease the retrieval of resources through deconstruction. The reduced variance of secondary materials could unlock new value streams through their sale, remanufacturing, and recycling, further driving CE's market competitiveness. As business cases improve, funding and management support could be reinforced and incentivize more stakeholders to pursue circularity. The competitiveness of secondary material prices and increased data availability could further drive the secondary market, alleviate profit pressure, and address one of the key cultural barriers: the preference for virgin materials. Overall, product platform principles align with CE strategies, e.g., Design-for-X, and present economic incentives for CE (Eberhardt, Birgisdottir, & Birkved, 2019; Machado & Morioka, 2021).

We will exemplify this enabler with the carpet supplier to the hotel module's interior. The strategic partnership with the developer allows the carpet supplier to realize scale economies. Lower unit costs allow investment into more sustainable options, which might otherwise have a cost premium. Standardized floor plan options allow optimized ordering and precutting, reducing assembly time, cost, and waste because the process and quantities have been predefined and vetted by the platform orchestrator and complementors. This process and the documentation of findings from completed projects increase production and assembly efficiency. Product platforms can also store material passports, when available, making it easier to support public reporting and guide end-of-life decisions. For example, carpets could be reused as insulation materials, creating a new circular business model and enabling their integration into another supply chain.

4.2. Reuse

Product platforms constrain the solution space and enable adaptability by building necessary "freedom into the design. Accordingly, a particular subsystem is engineered with room to grow" (Meyer & Lehnerd, 1997, p. 88). These principles complement design-for-X strategies, such as design-for-deconstruction, which are among the main metrics to measure and guide circularity in designs (Sassanelli et al., 2019; Benachio et al, 2020). Adaptability leverages interface reversibility defined as "the effort to reverse, or disconnect" (Fixson, 2005, p. 359). The depth of adaptability varies with the degree to which designs entail standardization, enabling different CE strategies outlined by Kirchherr et al. (2023): maintenance, upgrades, add-ons, adaptation, refurbishment, and reuse of materials, components, modules, or entire buildings (Mhatre et al., 2021). Adaptability can thus defer the end-of-life, facilitate non-destructive deconstruction, quality maintenance, and maximize reuse potential (Minunno et al., 2018; Machado & Morioka, 2021; Liu et al., 2015). Deconstructing instead of demolishing ultimately

Table 5
Overview of CE Barriers mapped to Product Platform Benefits.

Phase(s)	CE Barriers	Product Platform Benefits				
		Documentation & Information Flow	Repetition & Learning	Efficiency	Economies of Scale & Reduced Costs	Adaptability
All	**Cultural Barriers**					
All	Uncertainty & Risk		D		C	D
All	Hesitant Culture					
All	Profit Pressure			C	C	
All	Lack of Awareness					
All	Linear Thinking					
Design/ Maintenance	Preference for Virgin Materials			C	C	
Design/ End-of-Life	**Market Barriers**					
Design/End-of-Life	Lack of Demand & Supply				C	
Design/ End-of-Life	Lack of Scale		C	C	C	
Design/End-of-Life	**Financial Barriers**					
Design/ End-of-Life	Low Competitiveness			C	C	
Design/ End-of-Life	Lack of Funding & Business Case			C	C	
Design/End-of-Life	Lack of Incentives				C	D
Design/End-of-Life	High Cost		C	C	C	
Design	Long-term Profits of CE					D
Design/End-of-Life	Cost for Reverse Logistics			C	C	R
All	**Knowledge Barriers**					
All	Lack of Practical Knowledge	I	D			
All	Lack of Data	I				
Design/End-of-Life	Lack of Professional Skills		D			
All	Lack of Systems, Guidelines, Standards	I	D			
All	Lack of Shared Understanding	I				
All	**Managerial / Organizational Barriers**					
All	Lack of Management Support				C	
Design/End-of-Life	Additional admin. & legal Requirements	C				
Design/ Construction/End-of-Life	Unsupportive Warranty Structures					
Design	Future Uncertainty					D
Design/End-of-Life	Lack of CE Indicators					
All	**Regulatory Barriers**					
All	Lack of Policies, Standards					
End-of-Life	Lack of Infrastructure					
Design/End-of-Life	Lack of strict Penalties & strong Incentives					
All	Inflexibility hinders innovation					(I)
Design/ End-of-Life	**Technological / Technical Barriers**					
Design/End-of-Life	Immaturity of Technology					
Design/End-of-Life	Lack of Innovativeness	I	I			
End-of-Life	Complexity of Deconstruction	C + R				R
Design/End-of-Life	Lack of enabling Digital Technology	C				
All	**Supply chain Barriers**					
All	Fragmentation	C + R				
All	Lack of Information Flow	C				
All	Insufficient Collaboration	I				
All	Involvement of Additional Players					
End-of-Life	Complex Reverse Logistics	C + R		C		R
All	Lack of Understanding of new Roles					
All	Lack of Support & Involvement					

lowers the required reprocessing to reuse and decreases the added complexity as well as costs of reverse logistics (Minunno et al., 2018).

In industrialized construction, which largely operates by product platform principles, standardized components and processes enable information flow to support CE (Kedir et al., 2023), as "modular constructions, prefabricated offsite constructions, and standardized elements help circular reuse of buildings and its components" (Kazmi & Chakraborty, 2023). Product platforms can house critical material information essential to determining direct reusability within the same product platform or in other products designed around reuse materials or components. This documentation often comes in the form of a passport associated with materials, components, or products. While material passports allow "data to be tracked throughout the product and building life cycle" (Berglund-Brown et al., 2022), barriers to material passport implementation include supply chain fragmentation that prevents sharing of information and lack of digitization and standardization to make information more actionable (Kedir et al., 2023), both of which could be aided by the use of product platforms.

To illustrate this enabler, we focus on the module's timber structure, where walls are joined using reversible connectors. These connectors allow for targeted maintenance, for example, if a wall is damaged, it can be partially dismantled and repaired without replacing the entire structure. At the end-of-life, the structural elements can be deconstructed and retrieved without major quality losses. With high levels of documentation for the module's structural system, the data on materials and dimensions as well as the standardization can help reintegrate structural elements into secondary markets without major reprocessing at end-of-life. Depending on local regulations, the wood could be reused for other structural uses or as non-structural cladding. Data availability creates opportunities for other stakeholders to design new dwellings with materials to be retrieved even before deconstruction (i.e. buildings as material banks), which additionally addresses storing issues.

4.3. Derisking

As outlined in section 3.1, the implementation of CE in construction is challenged by risk aversion and perceived uncertainty connected to CE. In their seminal work on product platforms, Meyer and Lehnerd (1997, p. xii) conceptualize risks as "the chasm of uncertainty", which can be bridged by the "arch of platform thinking". As such, financial, planning, and market risks "can be minimized with wider scale CE application" (Hossain et al., 2020, p. 11), which can be facilitated by product platforms.

Firstly, product platforms help address financial risks by reducing overall running costs as they "make it possible for firms to create derivative products at incremental cost relative to initial investments in the platform itself" (Meyer and Lehnerd, 1997, p. 41). Adaptability reduces assembly time, minimizes energy losses, and reduces design and redesign costs incurred by future changes, lowering financial risks of and barriers to CE (Sawhney, 1998; Machado & Morioka, 2021).

Until now, circular solutions remain underexplored in construction. If development of new CE solutions proceeds and ways of constructing circular are being tested, standardized and reapplied capabilities are built through continuous documentation and learning, addressing the lack of skills, practical knowledge, guidelines, and standards. The storage of best practices and their repetition can unlock learning effects, reducing errors and uncertainties connected to CE, addressing both financial and planning risks. Further, "standardization provides reliability and safety by lowering risks, creates a common level of knowledge (…) and provides a universal view on different issues" (Anastasiades et al., 2021, p. 8). Reduced fragmentation along the supply chain can lower risks of decision deferral, misunderstanding, and conflict across design and construction phases, which typically result in rework, resource waste, and additional costs (Chen et al., 2022). As a result of standardization, the predictability of specifications, processes, schedules, and cost is likely to increase (Kazmi & Chakraborty, 2023), reducing planning risks of CE. Building a solution space of verified CE approaches supported by product platforms can thus address management barriers, like the lack of proven tools, systems, guidelines, standards, and cultural barriers regarding uncertainty and risk.

Product platforms enable adaptations to unforeseen circumstances, e.g., fluctuations in demand and functional use, lowering market risks, including asset redundancy and sunk costs (Allahaim et al., 2010; Pomponi & Moncaster, 2017). The "reduction of this uncertainty and risk can be realized by moving beyond the creation of project-specific unique solutions" (Veenstra et al., 2006, p. 170) to adaptable solutions. Spearheading works (e.g. Greden & Glicksman, 2005; De Neufville et al., 2006) suggest that adaptability can increase financial valuations of constructions, as it enables future real options, through which developers can react to market changes. Further, adaptability could reduce risks of financial losses due to early demolition, high vacancy rates, and low return on investment (Baldi, 2013; Ross, 2017; Wang, de Regel, Debacker, Michiels, & Vanderheyden, 2019). These increased valuations could address financial barriers to CE, as profits of CE typically lie in the long term, and set incentives for adaptability, which is tightly connected to Design-for-X strategies. The unfolding of the abovementioned dynamics depends on contextual factors, such as the extensiveness, timing, and costs of adaptations, as well as the valuation methods applied, suggesting detailed analyses through, e.g., real-options engineering for decision support (Throupe, Stephen, Zhong, & Chen, 2012). While the relationship between adaptability and CE has been acknowledged, and some studies have examined financial valuations of adaptability, investigations directly including CE remain unexplored until now.

In the context of our example, we assume a drop in hotel demand, prompting the platform orchestrator to adapt the hotel into student housing. As the platform architecture leverages Design-for-X principles, this adaptation requires less effort, time, and cost, while reducing the need for additional materials to transform the building. Strategic partnerships with contractors, such as manufacturers, help reduce the risks of errors and miscommunication, as stakeholders gain experience and build shared knowledge, even when working with new product variants like student housing or hotels. Each transformation project contributes to a growing body of documented, replicable and continuously optimized learnings. When building use changes, standardized and reversible interfaced make it possible to swap out individual parts, entire modules or even larger building systems. These flexible adaptations create potential future real options, which can increase the building's value and lead to higher margins throughout the supply chain.

4.4. Innovation

One of the central technological and technical barriers to CE is the limited capacity to innovate, which is exacerbated by knowledge barriers and the lack of collaboration. Based on the reviewed literature, product platforms support knowledge creation, accumulation, transfer, specialization, and optimization. These benefits may also enhance firms' capacity to innovate and explore new approaches to circular construction. In this context, documentation can address the absence of knowledge management systems, fostering continuous and incremental innovation (Halman et al, 2008; Thuesen & Hvam, 2011).

Product platforms can lower fragmentation, hindering the systemic uptake of innovations (Hall et al., 2020). Their focus on documentation, data storage, and sharing can further foster conditions for systematic collaboration (Gawer, 2014), a core necessity and barrier to CE (Bressanelli et al., 2019; Elia et al., 2020; Sudusinghe & Seuring, 2022). Enabling data to flow more readily between stakeholders creates communication channels to bridge "the traditional divide between engineering and manufacturing with the result that both products and processes for creating them were simultaneously redesigned" (Meyer & Lehnerd, 1997, p. 15). In contrast to less integrated projects, projects with a high stakeholder integration increase the likelihood of 'green' systemic innovations (Katila et al., 2018; Leising et al., 2018). As platform openness increases, so does access to "innovation agents and their diverse capabilities" (Gawer, 2014, p. 1244). Additionally, product platforms "support business model innovation and provide opportunities for the creation of new organizational forms" (Aksenova & Oti-Sarpong, 2024), necessary to successfully implement CE in construction.

The core-periphery model is "based on the concept of modularity which allows variety, scalability and diversity of components necessary for innovation" (ibid, p.4). By reducing interdependencies, simplifying interfaces, and reducing the information necessary for designers, product platforms allow innovative recombination of modules (Gawer, 2014). Innovative product variants can be achieved without reinventing each variant, instead, modularity enables incremental changes, redesign, and the addition of modules (Machado & Morioka, 2021). Knowledge, design rules, and processes are built into the product platform, freeing designers' capacities to innovate. Non-platform approaches leave "too little time for being innovative and for developing new products" (Harlou 2006, p. 15), a key technological barrier to CE. Although product platform benefits cannot directly impact regulations that challenge innovativeness, they can support innovativeness directly.

In our example, the developer might choose to create subsequent versions of the module as user needs, product availability, or regulations change. The standardized interface design, design-for-variety, design-for-deconstruction, and core product design can allow for innovations to be integrated into the module. With the bulk of the module design being set, complementors of the product platform can focus their efforts on ways to improve module performance, e.g., environmental, financial, or user satisfaction.

5. Discussion

5.1. Product Platforms as a Systemic Management Approach for Circular Economy

This review suggests that product platforms could serve as a systemic management approach to CE in construction by integrating building phases and stakeholders along supply chains, while also offering potential solutions to key CE barriers. A recurring pattern is the need to standardize construction (e.g., Anastasiades et al., 2021; Oluleye et al., 2022; Sajid et al., 2024). Construction's characteristics, including hyper-fragmentation, long lifecycles, and the need for customization, challenge the objective to make construction "more like manufacturing" (Aksenova & Oti-Sarpong, 2024). Based on this study, we argue that standardizing components but also realizing economies of repetition in knowledge, processes, and partnerships can be valuable to enable mass-customization of buildings (Davies & Brady, 2000). Product platforms provide a suitable frame to apply standardization without over-limiting architectural freedom. Research already positions standardization and modularization as supportive to CE; they, however, lack systemic logic brought forth by product platforms. Product platforms present a systemic management approach that can drive integration along supply chains, projects, and phases, as CE calls for (Oluleye et al., 2022). In line with Lessing et al.'s (2005) illustration of eight categories as a proxy for the level of implementation of industrialization, we found that product platform implementation is not a binary choice, but a mindset according to which repetitions can manifest across different domains (components, processes, knowledge and partnerships) to varying degrees.

5.2. Integration Across Phases

In the design, product platforms predefine a solution space considering various perspectives along the supply chain while equipping components with data to enable the "domino effect" of standardization. The coordination between designers and demolishers is particularly relevant to prepare components for reuse through Design-for-X, e.g., for deconstruction. During construction, data transparency and predictability can increase efficiency, reduce complexity, and improve informed decision-making. During operations, product platforms enable uncomplex refurbishment and adaptations to dynamic functional uses. At the end-of-life, investments into Design-for-X pay off as standardized materials and components can be retracted at a high quality, or buildings' uses can be altered. Product platforms promote standardization, low variance, and high predictability of secondary materials making it easier to reintegrate them into secondary markets. These recovered materials can either be taken back and reintegrated into the same product platform or serve as input for different supply chains. Overall, product platforms can support circular construction in embracing lifecycle thinking to support a systemic reduction of resource needs (Bressanelli, Visintin, & Saccani, 2022; Kirchherr, Yang, Schulze-Spüntrup, Heerink, & Hartley, 2023; Gamage et al., 2024).

5.3. Integration across the Supply-Chain and Industry

In closed platform approaches, product platform benefits can enhance company-level integration, such as internal reverse logistics, closed loops, and innovativeness (Elia et al., 2020). Given the fluid nature of openness, these benefits may extend from the supply chain to the broader industry (Gawer, 2009). Although this shift involves complex dynamics beyond the scope of this study, we highlight potential pathways for such extrapolation. While components and processes are typically supply chain dependent, they serve as reference points for external stakeholders to align their components and processes accordingly. For example, a solar roof panel supplier can design systems compatible with standardized, shared roof specs, enabling installation without further customization. This "domino effect of standardization" benefits both the supplier and the connected supply chain. Strategic partnerships – and the processes and knowledge they generate – can span multiple supply chains. In the construction sector's web of inter- and intraorganizational connections, benefits that unfold in individual organizations, supply chains, or partnerships can inspire broader industry change.

5.4. Identified Gaps

This integrative review theoretically connects CE with product platforms in construction, highlighting several empirical research opportunities. Firm-level use of product platforms may influence CE implementation at the industry level, for example by linking design and end-of-life, improving data availability, and enhancing supply chain collaboration (Bressanelli, Perona, & Saccani, 2019; Elia, Gnoni, & Tornese, 2020; Sudusinghe & Seuring, 2022). Investigating industry coordination whether and how these benefits scale to the industry (Aksenova & Oti-Sarpong, 2024; Elia, Gnoni, & Tornese, 2020; Sudusinghe & Seuring, 2022). These investigations should examine potential competition over platform orchestration/ownership (Baldwin and Woodard, 2009), which may widen gaps between small and large companies (Köhler et al., 2022) and explore increased fragmentation between companies adopting product platforms and those that do not (Aksenova & Oti-Sarpong, 2024).

Although product platforms may help address several barriers to CE in construction (Table 5), some dynamics, such as their effects on financial risk, costs and resource savings, require further exploration. Some barriers remain unaddressed (Table 6) and potential indirect effects require deeper investigation. Regulatory barriers warrant particular attention. Strengthening regulations for standards could support product platform interoperability at the industry level (Anastasiades et al., 2021), as attempted by the British government's funding of research on how product platforms help boost "productivity, innovation, and quality" in construction (Construction Innovation Hub, 2022).

We found the fundamental principles of platform thinking integrated into many tools in construction, e.g., industrialized construction, configurators, parametric modelling, design-for-disassembly, BIM, and material passports. Despite some research connected some of these tools to CE, platform thinking presents a broader mindset focusing on identifying economies of repetition in components, processes, knowledge, and partnerships. In this way, it serves as an overarching framework encompassing these tools. Tools that could support the knowledge domain include industry 4.0 technologies, such as block-chain, cloud sharing, and big data (Taddei et al., 2022; Sassanelli et al., 2023; Rosa et al., 2020). As the construction sector "resists cross-disciplinary or 'systemic' innovations" (Kedir et al., 2023) due to fragmented supply chains, the ICT could support information flows that are fundamental to supply chain integration and the recirculation of materials (Sudusinghe & Seuring, 2022; Acerbi et al., 2022; Elia et al., 2020; Bressanelli et al., 2022).

In current interpretations of product platforms, the partnership domain is rarely addressed, overlooking the potential long-term partnerships to reduce industry-fragmentation (Bressanelli, Visintin, &

Table 6
CE barriers without identified direct effects of Product Platforms.

Phase(s)	CE Barriers
All	**Cultural Barriers**
All	Hesitant Culture
All	Linear Thinking
All	**Managerial / Organizational Barriers**
Design/Construction/End-of-Life	Unsupportive Warranty Structures
Design/End-of-Life	Lack of CE Indicators
All	**Regulatory Barriers**
All	Lack of Policies, Standards
End-of-Life	Lack of Infrastructure
Design/End-of-Life	Lack of strict Penalties & strong Incentives
All	Inflexibility hinders innovation
Design/End-of-Life	**Technological / Technical Barriers**
Design/End-of-Life	Immaturity of Technology
All	**Supply Chain Barriers**
All	Involvement of Additional Players
All	Lack of Understanding of new Roles
All	Lack of Support & Involvement

Saccani, 2022; Kedir et al., 2023; Berglund-Brown et al., 2022). Seeking repetitions in this domain could address more barriers and cover growing literature on strategic partnerships, alliancing, and supply chain integration (Sudusinghe and Seuring, 2022; Elia et al., 2020; Jones et al., 2022). Integrating the 'organizational domain' would align with modularization literature, which highlights organizational design as a key factor in promoting specialization (Campagnolo & Camuffo, 2010). An overview of the suggested avenues for future empirical research can be found in Table 7.

6. Conclusions

This study has explored the potential of product platforms to address the barriers to CE in construction. The integrative review of CE barriers and product platform benefits has provided the first theoretical insights into the interlinkages of both areas. Firstly, we synthesized the barriers to CE in construction in 8 categories: cultural, market, financial, knowledge, management & organizational, regulatory, technological & technical, and supply chain. Secondly, we outlined the application of product platforms in construction, according to which they are conceptualized by a technical, process, and knowledge domain. Based on this delineation, we synthesized 5 benefits of product platforms in construction: documentation & information flow, repetition & learning, efficiency, scale economies & reduction of costs, and adaptability.

After mapping CE barriers to product platform benefits, we identified four enablers that address CE barriers in construction: *Commercialization*, *Reuse*, *Derisking*, and *Innovation*. Firstly, product platforms can support the commercialization of CE in construction, as they can induce scale economies, efficiency, and learning while unlocking new value streams. Secondly, product platforms can support the reuse of resources, as standardization and modularization can enable CE strategies, such as design-for-x and extension of buildings' lives. Thirdly, product platforms can lower market, financial, and planning risks of CE, as costs are reduced, capabilities are strengthened, and adaptability to unforeseen circumstances is enabled. Lastly, leveraging information flows, product platforms can liberate space for collaboration, align supply chains, and thus foster innovativeness. Although we found that product platforms can address a wide range of CE barriers, several barriers, specifically regulatory ones, remain largely unaffected.

Our review indicates that although product platforms are not a silver bullet to all CE barriers, they can present a systemic management approach to support firms in decision-making that enables circular construction within supply chains. Further, product platforms can provide opportunities to integrate CE-enhancing technologies such as automation, prefabrication, and material passporting. This study attempts to build a foundation that allows future research to continue developing the insights and identified gaps to progress the challenging

Table 7
Suggestions for Future Research.

Further Research	Research Questions
Distribution of Product Platform Benefits	How are benefits created by product platforms distributed along the supply chain?
Circular Economy in the wider system	Does standardization through product platforms support the creation of new business models based on secondary materials?
Product Platforms across construction industry	What are dynamics of product platform implementation (for the Circular Economy) in construction over time?
Product Platform Competition	What impact does the implementation of product platforms have on competition dynamics in the construction industry?
Product Platform Fragmentation	Does the implementation of product platforms increase fragmentation between companies that work within versus outside of product platforms?
Regulatory Barriers to Circular Economy	How can product platforms address regulatory barriers to the Circular Economy in construction?
Orchestrating Product Platforms inConstruction	Which stakeholder or combination of stakeholders are most suitable to orchestrate product platforms in construction to ensure successful implementation of the circular economy?
Platform Orchestrator	What are suitable governance and control mechanisms for the platform orchestrator to maintain freedom for complementors, but ensure interoperability?
Cultural, Managerial, and Supply chainBarriers to the Circular Economy in Construction	Does the implementation of product platforms have further indirect effects on cultural, managerial, and supply chain barriers, such as hesitant culture, persistent linear thinking, and lack of support and involvement?
Integration of ICT	Can product platforms act as a suitable integrator for ICT tools (configurators, BIM, parametric modelling, material passports) in construction?
Industry 4.0	How can Industry 4.0 technology support the knowledge domain of product platforms?
Organizational Design	How can product platforms unfold benefits by organizational modularity, through e.g. the modularization of partnerships?
Product Platforms as Enablers forCommercialization of Circular Economy	How can product platforms support the development of new business models, based on e.g. secondary material streams to improve the business case of circular economy in construction?
Product Platforms as Enablers for Reuse	How can product platforms in construction facilitate the reuse of building materials by overcoming key barriers and integrating reverse logistics?
Product Platforms and Take-Back-Systems	How can the implementation of product platforms in construction support the reuse of materials through take-back-systems?
Product Platforms as Enablers for RiskManagement	How can Design-for-Adaptability enable a circular economy in construction by reducing risk?
Product Platforms as Enablers forInnovation and Learning	How can product platforms in construction reduce fragmentation and foster innovation for the circular economy?

yet promising application of product platforms in construction. Notwithstanding, we acknowledge shortcomings of our study. Although the study was designed to identify relevant studies, other relevant papers might require consideration. As the aim was to develop first insights, additional investigations are needed to deepen the outlined discussion. Further, this study only represents theoretical discussions, which require empirical testing.

CRediT authorship contribution statement

Julia Köhler: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amy Marianne Egerter:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Daniel M. Hall:** Supervision, Project administration. **Christian Thuesen:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Appendix A:. Coding outline

Contextual Factors	Cost Culture in AEC Customer Focus / Understanding Economic Conditions Fragmentation Nature of Market Policy / Regulations Product Design Roles & Responsibilities IT / Software Supply chain
Flows	Financial Flow Information Flow Material Flow
Potential Link to the Circular Economy	9Rs Business Models for CE Design for Disassembly Emissions Reduction General Link Material Passport Modularization Standardization Waste Reduction
Product Platform	Barriers Enablers Benefit Drawbacks Collaboration & Partnerships Efficiency Knowledge Domain Technical Domain Process Domain Implementation Maintenance Customer Decoupling Point Mass Customization Interface Design Rule
Type of Platform	Data Base Design Configurator Marketplace Other Types of Platforms Product Platforms

Data availability

No data was used for the research described in the article.

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