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The role of digital technologies in configuring circular ecosystems

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Abstract

Purpose – This paper aims to explore the use of digital technologies in enabling circular ecosystems. We apply supply network (SN) configuration theory and a novel resource pooling lens, more typically used in financial systems, to identify inventory pools, information repositories and financial exchange models among network actors.

Design/methodology/approach – Five in-depth circular SN case studies are examined where digital technologies are extensively deployed to support circularity, each case representing alternative SN configurations. Data collection involved semi-structured interviews to map SN and resource pooling configurations across each circular ecosystem, with cross-case analysis used to identify distinct pooling and digital strategies.

Findings – Results suggest three digitally enabled circular ecosystem archetypes and their related governance modalities: consortia-based information pooling for resource recovery, intermediary-enabled material and financial pooling for remanufacturing and platform-driven information, material and financial pooling for resource optimisation.

Research limitations/implications – Drawing on SN configuration and resource pooling literature, we recognise distinct configurational, stakeholder and resource pooling dimensions characterising circular ecosystems. While this research is exploratory and the identified archetypes not exhaustive, the combination of resource pooling and configuration lenses offers new insights on circular ecosystem configurations and the critical role of resource pools and enabling digital technologies.

Practical implications – We demonstrate the utility of the resource pooling and configuration approach in the design of digitally enabled circular ecosystems. These archetypes provide practitioners and policymakers with alternative design frameworks when considering circular SN transformations.

Originality/value – This paper introduces a resource netting and pooling configuration lens to circular ecosystems, analogous to financial systems, where cyclical flows and stock are critical and enabled through digital technologies.

Keywords Circular ecosystems, Supply network configuration, Stakeholder theory, Digital transformation

Paper type Research paper

Introduction

Rising concerns over material scarcity have led to the emergence of circular value-capture models to reduce primary raw material consumption (Ellen MacArthur Foundation, 2012). Although various circular economy initiatives and policy interventions exist, it is widely accepted that significant operational challenges remain in transitioning to a circular economy. The rising popularity of circularity led to the emergence of multiple interpretations of its concept making it an "essentially contested concept" (Korhonen *et al.*, 2018). Furthermore, much of the literature does not address the fundamental systemic shift required for implementing circular transformation strategies (Kirchherr *et al.*, 2017), which is increasingly recognised by scholars as indispensable (Kirchherr *et al.*, 2023). Moreover, Kirchherr *et al.*

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(2023) demonstrate the evolving nature of the circular economy noting that there may never be consensus over its definition. This lack of a common understanding of the circular economy concept among academics, practitioners and policymakers creates operational challenges and limits industry adoption (Bressanelli *et al.*, 2018). For instance, the Circularity Gap Report (2023) disclosed that in 2022 only 7.2% of resources used in manufacturing are recycled or recovered, which represents a reduction from 8.6% (2020) and 9.1% (2018) in previous years. This decline underscores the inadequacy of continuous improvement approaches, which are likely insufficient and highlights the necessity for more radical solutions to drive circularity.

A key dimension in moving to circular ecosystems is the underpinning circular supply networks (SNs) and information technologies that reshape product supply chain boundaries and redefine network relationships (Porter and Heppelmann, 2014). For example, the World Economic Forum suggests a potential 20% reduction in emissions through the adoption of digital technologies (WEF, 2022). Furthermore, digital technologies offer great potential to facilitate new forms of collaboration and information exchange across distributed networks of diverse actors (Vial, 2019). Especially in the context of circularity, digital technologies integrated via digital platforms can provide the necessary information on resource flows across product life cycles to inform end-of-life recovery solutions (Antikainen *et al.*, 2018). Moreover, digital technologies can support the development of circular ecosystems through the identification of complementarities in the form of resource flows among ecosystem actors (Mathews *et al.*, 2018).

Despite evidence of the potential for digital technologies to incentivise circular business models (Okorie *et al.*, 2021) and overcome circular economy challenges (Bressanelli *et al.*, 2018), their effective deployment within product manufacturing life cycles and business processes is not well understood (Zheng *et al.*, 2021). Furthermore, Kristoffersen *et al.* (2020) highlight the lack of systematic approaches in the implementation of circular strategies that leverage data collection, analytics, integration and sharing at an operational level. We address this gap in the literature by exploring the research question: “How might the use of digital technologies enable circular ecosystems?”. Specifically, we examine how digital technologies enable circular SN configurations as a central idea in circular ecosystem design.

We leverage research on SN configuration (Srai and Gregory, 2008) and introduce it to the circularity context by expanding on SN coordination using material, information and financial flows (Eltantawy *et al.*, 2015). Furthermore, we recognise that one critical aspect of circular ecosystems is the ability to track and manage resources to ensure the availability of stock and capital for subsequent reprocessing. To address this aspect, we draw on approaches used in financial management, where resource netting and pooling are necessary for the efficient use, reuse and tracking of financial stocks (Hofmann, 2007). Therefore, we consider resource netting and pooling principles in order to complement SN configuration theory in the circularity context because it acknowledges the value of aggregating resources – i.e. material, information and financial – to improve exchanges among circular ecosystem actors with the support of digital SN technologies.

In this research, these two lenses of SN configuration and resource pooling are used to explore exemplary applications of digitally enabled circular ecosystems. In each case, we explore effective forward and reverse material flow management via inventory pools, information exchange through digital platforms and alternative value generation models among multiple actors (Boldrini and Antheaume, 2021; Yang *et al.*, 2018).

The next section examines four main bodies of literature within our circular ecosystem context, namely SN configuration, stakeholders, ecosystems and the role of digital technologies and platforms, leading to the development of a conceptual framework. Cross-case analysis methods are then used to reveal first- and second-order configurational, stakeholder and digital technology attributes to identify pooling patterns across different circular ecosystem archetypes. Finally, we discuss the different resource pooling configurations with their related ecosystem governance modalities and the implications of the approach for practitioners and policymakers.

Literature review

A transition to a circular economy needs to capture value at an ecosystem level through both circular business models and circular SNs (Geissdoerfer *et al.*, 2018). Furthermore, the ecosystem informs the positioning of stakeholders and their relationships while the business model provides the operational and economic architecture that ensures the ecosystem is financially self-sustainable (Low and Ng, 2018; Moggi and Dameri, 2021). Circular business models drive SNs in different closed-loop configurations, namely closed, dematerialised, intensified or narrow loops (Geissdoerfer *et al.*, 2018).

Examples of circular business and operating models include collaborative sharing, product-as-a-service and end-of-life valorisation, such as recycling, remanufacturing, refurbishing or reuse (Gavrila Gavrila and de Lucas Ancillo, 2021). The benefits of circular adoption are new possible income sources and extended market reach. Circular business models can capture non-traditional value beyond profit including data generated, brand recognition and unique production processes with highly customisable services (Okorie *et al.*, 2021). These new revenue models are enabled by servitisation where customers are charged for access while the original manufacturer retains product ownership; hence, the latter is incentivised to prolong the longevity of their assets (Pawar *et al.*, 2009). Such product-service systems' business models can enhance the circularity of SNs (Yang *et al.*, 2018). Nevertheless, the operations management community has had limited engagement with circularity concepts, often with a skewed theorisation lacking a SN perspective (Marques and Manzanares, 2023).

Furthermore, several authors have demonstrated the fundamental role of SN design considerations in the successful implementation of circular practices, e.g. the level of SN integration (Calzolari *et al.*, 2021), renewable feedstock-driven reconfiguration (Srai *et al.*, 2018), reverse networks for end-of-life recovery (Rentizelas *et al.*, 2021) and multi-stakeholder network collaborations for value chain engagement (Brown and Bajada, 2018). However, digitalisation has only been recently introduced as a circular economy enabler, primarily in the context of new business models (Jabbour *et al.*, 2019; Kristoffersen *et al.*, 2020; Okorie *et al.*, 2021). We build on the work of Rajala *et al.* (2018) who explored the influence of goods-related intelligence on the configuration of closed-loop ecosystems and underscored the need for more empirical research also covering multi-actor platforms. In addition to understanding digital technology influences on circular business models, we consider how they affect circular SN design and operations.

This section covers the literature concerning digitally enabled circular ecosystems, which is spread across various bodies of literature and schools of thought. Four pivotal bodies of literature are considered to capture various viewpoints: SN configurations, stakeholder interactions, ecosystems and digital infrastructure, including technologies and platforms.

Supply network configuration perspective

SN configuration and integration are considered prerequisites for the implementation of new SN management initiatives (Danese *et al.*, 2006), in this case, circular SNs. For instance, configuration analysis can provide a better understanding of the types of interactions between network actors (Samaddar *et al.*, 2006) and their value-creation mechanisms (Chakkol *et al.*, 2014). Such interactions occur in the form of material and knowledge flows, which dictate SN performance. The increasing complexities associated with these flows and exchanges require managerial capabilities (Macchion *et al.*, 2015). Srai and Gregory (2008) demonstrated the link between SN configuration and organisational capabilities, further emphasising their importance.

Drawing on Srai and Gregory (2008), the four dimensions of configurational analysis outlined are network structure, material and information flows, product or service "value structure" and network actor relationships. These have been revisited and adapted to the context of circularity. Firstly, network tier structure in the circularity literature is discussed in terms of complexity (Lambert and Enz, 2017; Matos and Hall, 2007), level of centralisation and geographical dispersion (Tsolakis *et al.*, 2020), as well as production processes and technologies (Srai, 2017). Secondly, knowledge of material and information flows among actors across the SNs including institutional, industrial and product SN actors (Srai, 2017; Srai and Alinaghian, 2013) is essential for forming closed loops and optimising resource consumption (Pawar *et al.*, 2009). Third, product attributes and emerging technologies reshape SN configurations (Rezk *et al.*, 2016). In circular configurations, the product or service "value structure" is dependent on the product design for circularity and end-of-lifecycle recoverability (Batista *et al.*, 2023), i.e. durability, modularity, ease of disassembly, repairability (Savaskan *et al.*, 2004), embedded value, and volume of returns (Guide and Van Wassenhove, 2009). Fourth, in terms of network actor relationships, governance dynamics (Marques and Manzanares, 2023) and also cross-functional coordination within an organisation (Sudusinghe and Seuring, 2022) promote the shift to circular systems. The latter is particularly important in circular SNs because of the bidirectional nature of resource flows between buyers and suppliers where both "upstream-downstream" and "downstream-upstream" collaborations involve internal and external stakeholders (Batista *et al.*, 2023; Sudusinghe and Seuring, 2022).

Finally, the development of circular SN configurations demands an understanding of the interactions of SNs with their surroundings to redesign the input and output flows (de Souza *et al.*, 2019). This raises considerations regarding the interrelatedness of circular SN configurations and the flows of information, material (Pawar *et al.*, 2009) and finance (Kunz *et al.*, 2018).

Stakeholder perspective

The stakeholder perspective, introduced by Freeman (1984), focuses on the relationships between organisations and their stakeholders for the purpose of collaboration and value creation. Creating and managing a collaborative network of firms across product-service systems is particularly important to effectively deliver value to customers (Pawar *et al.*, 2009). Furthermore, effective coordination of stakeholders (Bajaj, 2017) coupled with holistic information sharing along the SN (Gupta *et al.*, 2019) is needed to achieve systemic change at scale for a circular economy. Moreover, preconditions to the successful creation of circular ecosystems are sharing knowledge, infrastructure, human resources and mutual trust (Moggi and Dameri, 2021). For example, relational mechanisms where interdependent firms collaborate to achieve a common interest have been shown to have a positive impact on resource efficiency and firm competitiveness (Kalaitzi *et al.*, 2019).

Stakeholder theory accounts for the perspectives of both commercial and non-commercial stakeholders including institutional and governmental players. External stakeholders such as regulatory bodies, communities and environmental groups can pressure organisations to adopt environmental practices (Sarkis *et al.*, 2010). One example is the Extended Producer Responsibility which makes manufacturers responsible for end-of-life product disposal (Kunz *et al.*, 2018). However, dominant organisations use power dynamics or hegemonic control in the network to influence institutional logic with their conceptualisation of sustainability and to restrict competing alternatives (McLoughlin and Meehan, 2021). In fact, multi-stakeholder alignment is extremely complex because of diverging interests, existing processes and activities and different understandings of value that require spanning across boundaries (Velter *et al.*, 2020). A key part of stakeholder management is the mapping of the identified and categorised stakeholders to further explore their interests, influence and mutual relations (Bendtsen *et al.*, 2021).

Ecosystem perspective

The concept of "ecosystem" has recently gained interest in strategy considerations to align interdependent organisations for creating and capturing new forms of value (Hou and Shi, 2021). The term, borrowed from biology, is used to describe groups of interacting and interdependent firms and is employed to depict the competitive landscape (Moore, 2006).

Adner (2017) defines an ecosystem as "the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialise". Such an ecosystem-as-structure view confines its boundaries to the value proposition shared across the group of actors and activities, giving rise to a clear strategy for their realignment and for securing their competitive positioning (Adner, 2017). Furthermore, ecosystem emergence is enabled by technological modularity because these multilateral non-generic complementarities facilitate coordination and allow firms to retain their independence without a hierarchical structure but with a standardised set of roles (Jacobides *et al.*, 2018). Hou and Shi (2021) suggest that these complementarities are created and sustained in communities of affiliated actors that openly exchange resources with the environment and stimulate innovation. Moreover, complementarities and relevant technologies must co-evolve across multiple organisations to secure the required resources and capabilities for continuous innovation (Moore, 2006).

The first step towards the transition to closed industrial loops or circular ecosystems is the identification of complementarities between all actors involved in the ecosystem (Mathews *et al.*, 2018). The orchestrator of the network plays a central role in detecting and managing these interdependencies and complementarities through formal and informal governance mechanisms that facilitate engagement, trust and continuous flows of resource and knowledge exchanges towards a common vision (Zucchella and Previtali, 2019). The orchestrator ensures the ecosystem contains a balance of heterogeneous actors across industry boundaries, namely, producers, consumers, scavengers and decomposers (Tate *et al.*, 2019). It is critical to visualise all parties and exchanges involved in the circular ecosystem in order to align their business models and connect relevant actors (Boldrini and Antheaume, 2021). Interactions within the ecosystem consist of information, material and financial flows, which require simultaneous and integrated management (Tate *et al.*, 2019). Platforms can be used to organise such interactions, enable connectivity and manage data flows within the ecosystem (Konietzko *et al.*, 2020) providing transparency and feedstock for circular processing.

Role of digital technologies and platforms

Digital technologies and platforms support circularity by providing data management capabilities to monitor, optimise and control resource movements (Moreno and Charnley, 2016). These comprise (1) data collection – the process of gathering data, e.g. through IoT, (2) data analysis – interpreting and understanding data, e.g. artificial intelligence, machine learning or big data analytics, (3) data integration – contextualising the data collected, e.g. cloud computing or big data, (4) data sharing – providing data to other parties, e.g. smart contracts and blockchain (Kristoffersen *et al.*, 2020) and (5) data aggregation for production – advanced manufacturing capabilities, e.g. digital design, additive manufacturing, virtual reality, automation and robotics (Berg *et al.*, 2020).

The integrated use of digital technologies can enable increasingly "servitised" offers and improve SN coordination and integration for better material flow management, leveraging the availability of decentralised real-time life cycle information (Zheng *et al.*, 2021). One example of this is the digital material or product passport which consists of an interoperable database (King *et al.*, 2023) containing securely stored information associated with goods throughout their lifecycle such as raw material specification, production processes and end-of-life guidance (Hoosain *et al.*, 2021) accessible to stakeholders across the value chain (Hakanen and Rajala, 2018). Furthermore, digital technology integration can improve SN coordination and control through smart purchasing and SN management (Srai and Lorentz, 2019) with real-time material track and tracing systems (Ivanov *et al.*, 2019).

At a product level, firstly, digital technologies allow for optimised eco-design that balances performance, modularity and end-of-life considerations with implications throughout the entire product life cycle from its production to its disposal (Garcia-Muiña *et al.*, 2019). Secondly, advanced processing technologies facilitate on-site repairs, adaptions and logistics supporting circular SN design with operations closer to the point of consumption (Srai *et al.*, 2020). Thirdly, data generated throughout the product service system life cycle (e.g. modelled via digital twin) allows preventive maintenance to extend the longevity of products and their components and also inform end-of-life decisions (Okorie *et al.*, 2021).

In addition, digital platforms are useful infrastructure to engage ecosystem stakeholders (Del Vecchio *et al.*, 2021) and foster collaboration in closed-loop systems (Rajala *et al.*, 2018) by unifying multiple systems across operations. For example, platforms facilitate the exchange of by-products for industrial symbiosis applications (Halstenberg *et al.*, 2017) as well as in online marketplaces matching supply-demand at warranted quality standards (de Jong and Mellquist, 2021). Furthermore, digital platforms can bridge "circularity holes", namely forming the missing linkages between waste producers and consumers, by taking on different brokerage roles (Ciulli *et al.*, 2020). To summarise, digital platforms enable new value-creation models that merge physical and digital systems to manage the flow of goods in closed-loop systems (Rajala *et al.*, 2018).

Finally, three categories of digital technologies enabling circularity are suggested in the literature: material-centric, product-centric and (digital platform) system-centric. In the case of material-centric, material status and intelligence are preserved with a unique identity and audit trail (Braungart *et al.*, 2007; Hakanen and Rajala, 2018) that provides information visibility and captures data as materials flow across ecosystem actors. Product-centric involves using data analytics for monitoring product utilisation for lifecycle extension to facilitate end-of-life product recovery and ensure equitable financial transactions (Porter and Heppelmann, 2014). The (digital platform) system-centric model connects the industrial ecosystem (Ghisellini *et al.*, 2016; Rajala *et al.*, 2018) by providing a circular e-marketplace for transactions across the product life cycle where products and payments are exchanged and related information is stored and made accessible. These three circular strategies, namely material, product and platform, display different layers of digital implementation that support circular material, information and financial flows; hence, they are used to inform the case selection criteria in the methodology.

Summary of the literature and conceptual framework

Interactions among ecosystems and their actors create complex social-ecological interdependencies that can be understood using network approaches (Bodin *et al.*, 2019). For instance, configuration analysis can provide a better understanding of value creation mechanisms (Chakkol *et al.*, 2014) and the types of interactions between network actors in the form of material (Braungart *et al.*, 2007), knowledge/information (Samaddar *et al.*, 2006) and financial (Hofmann, 2007) flows. The increasing complexities associated with these flows and exchanges require managerial capabilities (Macchion *et al.*, 2015). These are influenced by network configurations, namely network structure, product value structure and governance (Srai and Gregory, 2008). However, SN configuration and pooling theories do not expand sufficiently on the alignment of interests and influence among the stakeholders required to achieve systemic change for circularity (Bajaj, 2017) and on the enabling role of digital technologies (Antikainen *et al.*, 2018).

Mishra *et al.* (2018) distinguish circular SNs by their ability to track product and material flows as they re-enter the production chain after their first use cycle. In a circular economy, products at any stage of their life cycle become useful inventory, e.g. damaged stock for remanufacturing, returned stock for reuse or discarded material stock for recycling. The location and ownership of such inventory become critical to capture its value throughout multiple supply use-return cycles (Tsolakis *et al.*, 2020; Yang *et al.*, 2018). Access to real-time information regarding inventory availability throughout multiple use cycles allows for determining alternative revenue models that balance interests among the stakeholders involved. As such, the transition from product to service revenues impacts the role of designers, producers and service providers in the co-creation of value-generating and sharing models. For these circular business models to operate, the expected economic value of the residual resources and returned stock needs to be calculated and accounted for in companies' financial sheets. For instance, depreciation principles may no longer be applicable as products at their end-of-life can have increased in value through upcycling and shifts in raw material pricing. New financial netting and pooling models can reduce transaction inefficiencies by accounting for multiple product lifecycle movements and ensure equitable revenue shares for each stakeholder based on material and product usage information. This enables organisations to offset risks and payments within circular models by valuing end-of-life products at the corresponding raw material price.

In circular ecosystems, two important considerations identified in the literature were which actor(s) holds the inventory, i.e. stock of materials held as physical resources and which actors own the data repositories, i.e. stock of information or "material intelligence". These require understanding the transaction models that account for net transfers, i.e. equity between stakeholders, including ownership of stock and material/product data. We adapt the resource pooling approach (Hofmann, 2007) to consider net stock and related movements across circular networks, i.e. financial, information and material pooling. The resource pooling approach, illustrated in Figures 2 and 3, captures both configuration and resource pooling perspectives. Specifically, the approach explores (1) SN configuration and how it informs inventory pooling models, (2) stakeholder interactions and how they drive economic value exchanges and (3) the role of digital technologies and platforms in facilitating transfers of material and product data throughout the lifecycle. The approach is used to uncover resource pooling patterns by identifying value and data exchanges and the enabling intermediaries (brokers, platforms, etc, Ciulli *et al.*, 2020) in circular ecosystems. Therefore, we integrate SN configuration and resource pooling (Hofmann, 2007) theories by capturing material, information and financial flows among digitally enabled circular ecosystems and their stakeholders (see Figure 1).

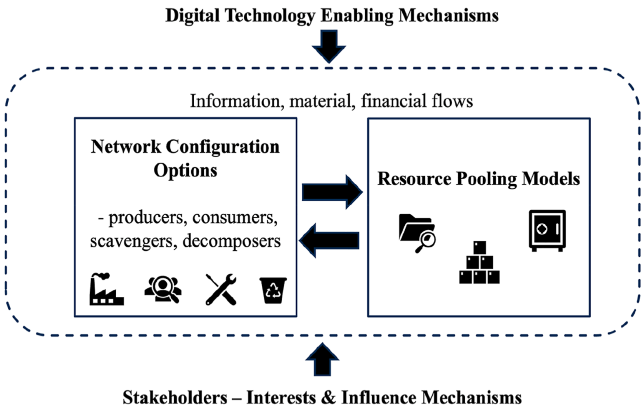

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Figure 1. Conceptual framing for exploring digitally enabled circular ecosystems

Design/methodology/approach

Given the limited literature concerning the role of digital technologies in circular SN design and the exploratory nature of this research, we undertook a multi-case study approach. The cases were analysed to understand configurational and stakeholder contextual influences on different digital circular ecosystems (Voss *et al.*, 2002). The circular ecosystem, which is the unit of analysis in this study, is defined by the cyclical product flows between network actors. Defining the network boundaries for case studies is notoriously challenging, particularly when exploring circular ecosystems consisting of several network actors exchanging value with dynamic and complex links (Halinen and Törnroos, 2005). Thus, we relied on the expert knowledge of multiple informants from the focal firm to define relevant internal, external and institutional network actors and their interrelationships. The actors were classified in terms of producers, consumers, scavengers or decomposers (Tate *et al.*, 2019) connected by resource exchanges, i.e. material, information and financial flows. Finally, we acknowledged the changing nature of circular ecosystems (Halinen and Törnroos, 2005) by investigating them in their current state while accounting for envisioned future state reconfigurations, i.e. dashed flows or actors.

Data collection

Data collection involved screening Multinational Enterprises (MNEs) to ensure the phenomena of interest, namely their circular ecosystems, were transparently observable (Pettigrew, 1990). Manufacturing MNEs were chosen as they are major global greenhouse gas emission contributors and they operate in multi-echelon networks, providing opportunities for information-rich cases (Griffin, 2017). Five MNEs were selected to support cross-case analysis (Eisenhardt, 1989; Halinen and Törnroos, 2005) that collectively met the case selection criteria, i.e. operate within the three – material, product, platform – categories of circular ecosystems, utilise digital technologies in their circular operations, represent alternative SN configurations and engage with progressive legislative contexts (e.g. the USA and EU for their more stringent environmental enforcement). For the material-centric category, we investigated two cases of material identification via product passports: a textile passport implemented by a US-based company and a battery passport led by a pre-competitive consortium of EU institutional bodies and private companies. For the product-centric category, two remanufacturing cases leveraging product monitoring were explored: a US MNE leader in construction equipment and a comparable EU MNE manufacturing heavy-duty vehicles. Finally, one MNE specialising in automation and energy management was selected for its circular take-back platform and resource exchange model and award-winning circular economy commitments.

Data was collected from June 2020 to September 2023 in the form of multiple respondent interviews and site visits for each case study, with respondent engagement following a snowball sampling approach until thematic saturation (Kvale, 1996). During the interviews, the respondents were guided in describing the circular operations with the aim of mapping the circular ecosystem in real-time using the data collection configuration and resource pooling framework in Figure 2 and as shown in the example in Figure 3. Facilitation proceeded in stages, starting with the identification of actors in the circular network, beginning with suppliers and then following the product through its life until its end-of-life recovery for reprocessing or disposal. The respondents validated material flows across the network actors while adding relevant information and financial flows, the approximate quantity inventory held and any additional functional actors. Consequently, the map was reviewed to ensure accuracy, to account for future flows and to investigate configurational and stakeholder influences. The research process and data collection protocol in Table 1 summarises the role of the respondents, the scope of the interviews, data collection, triangulation methods and the case selection rationale for each organisation.

Srai and Gregory (2008) suggest the use of mapping approaches for visualising complex SN configurations and for conducting transferable cross-sectorial data analysis. In Figure 2, we incorporate this approach to explore circular SN configurations and resource pooling patterns. Resources pools could be inventory (material), equity (finance) and data repositories (information). The map is inspired by the supply pooling approach for evaluating SN configurations (Srai *et al.*, 2022) and by e^3 value methodology for modelling e-businesses and ecosystems (Gordijn and Akkermans, 2001). Both methods combine business, economics and systems theories to depict actors exchanging economic value in different forms (Hofmann, 2007). In this research, we illustrate material, financial and information exchanges within the circular ecosystem to identify the existing SN and functional actors that are aligned toward a shared value proposition (Adner, 2017).

Table 1. Data collection protocol with selected case studies overview and inclusion rationale

Context	Respondents	Data collection method	Process and triangulation	Case selection rationale
Case 1: Textile passport				
Implementation of a digital garment passport at billion-dollar US fashion company level	Vice president of fashion company Material and fiber strategy lead at NGO Circular NGO director Environmental Manager at the resale platform	Ecosystem mapping for the textile industry ecosystem Interviews with industry and company circular leaders (total = 9 h)	Company view contrasted with perspectives from no-profit institutions in the circularity space	Material identification for retaining traceability (Company driven)
Case 2: Battery passport				
Digital battery passport for electric vehicles developed at a European level	CE and battery researcher at MNE Eco-design and circular economy engineer Sustainable mobility and battery lead for CE cars Battery life cycle expert	Ecosystem mapping for automotive EV circular ecosystem Interviews with company and initiative leaders (total = 8 h)	Factory visits, battery pass initiative reports, webinars, battery trend reports	Material identification for retaining traceability (Institutionally driven)
Case 3: US remanufacturing				
Construction equipment company world leader in reman (focused on parts – product identity lost)	Supply chain strategy director Lean digital procurement manager Business development and analytics manager	Ecosystem mapping for reman ecosystem, interviews with senior managers across divisions (total = 13 h)	Factory visits, company reports, digital supply chain consortium and interviews	Product condition monitoring for remanufacturing (All internal operations ~4k employees ~8k unique part numbers)
Case 4: EU remanufacturing				
Heavy duty vehicle manufacturer with extensive ranges of remanufactured products (product identity maintained after reman)	Senior global Remanufacturing engineer (x2) Director circular development Product manager (x4) Global core director	Ecosystem mapping for European remanufacturing Workshop involving 11 reman experts, follow-up interviews (total = 13 h)	Published company reports, company visits and in-person workshop, company websites	Product condition monitoring for remanufacturing (~70% external partners ~1k employees in Operations + 2-3k employees involved from R&D, Purchasing, Sales, etc., 5k + unique parts number)

(*continued*)

Context	Respondents	Data collection method	Process and triangulation	Case selection rationale
Case 5: Circular platform				
Automation and digital solutions company connecting products and software	SVP sustainability VP digital consulting VP global supply chain performance CE business consultant CE project lead (x3)	Interviews with experts leading digital or circular implementations (total = 11 h)	Digital supply chain consortium, WEF webinar on circular initiatives, factory visits	Platform for knowledge and resource exchange (~11k take-back ready product references)

Source(s): Authors' own creation

Data analysis

Data analysis was conducted using a deductive approach in two stages, namely within- and cross-case analysis. The within-case analysis aimed at understanding the dynamics and characteristics of each case study, which was then followed by a thematic cross-case analysis against the dimensions of the conceptual framework (Miles and Huberman, 1994). Firstly, the full-interview data transcripts were analysed through the development of a written narrative for each case study. The process of characterising each case study involved the in-depth analysis of the interview transcripts and supporting documentation to identify network configuration, stakeholder and digital platform dimensions characterising each case study. Secondly, all cases were coded simultaneously against the narrative developed for each first-order dimension to reveal second-order dimensions or theoretically rooted patterns. The cross-case analysis consisted of identifying recurrent themes and grouping them into conceptual categories as part of the theory-building process through a series of iterative comparisons (Miles and Huberman, 1994).

Several considerations and measures were taken to conduct transparent and credible research and minimise bias throughout the research (Eisenhardt, 1989), which we detail in this paragraph from the research design to its testing. At the design stage, we used a multi-stage sampling approach to select exemplar cases of digitally enabled circular ecosystems where the phenomenon was transparently observable and that satisfied the criteria set out earlier in the methodology in the Data Collection subsection. The multi-stage sampling approach consisted of (1) screening the grey literature to identify potential case study candidates, (2) conducting preliminary interviews with senior operations and/or sustainability directors to evaluate the case fit (we excluded pilots and small-scale initiatives) and willingness to participate in the research (3) defining the boundaries of each case study in terms of the specific circular ecosystem implemented and (4) successfully operating at scale. Subsequently, a replicable case study data collection protocol was developed for data collection and analysis via the resource pooling maps. Consequently, testing for construct validity, internal validity, external validity and reliability was applied to validate the findings (Yin, 2017). Construct validity was ensured through the use of multiple sources of evidence described in Table 1, both primary (i.e. interviews, site visits and workshops) and secondary data (i.e. peer-reviewed academic literature, industry reports, white papers and online articles), enabling data triangulation (Eisenhardt, 1989). Internal validity was achieved by performing both within- and cross-case analysis. Firstly, we developed a resource pooling map, narrative and first-order coding for each case, and then we compared the dimensions across cases to find second-order themes. External validity was attained using a replication logic when conducting the case studies and by consistently applying the case study protocol for data collection and analysis. Finally, checks for reliability involved follow-up discussions with informants after primary data collection via interviews to confirm the accuracy of the data and provide feedback on the data analysis. Based on follow-up discussions, revisions were made where required, further increasing the validity of both observations and the findings.

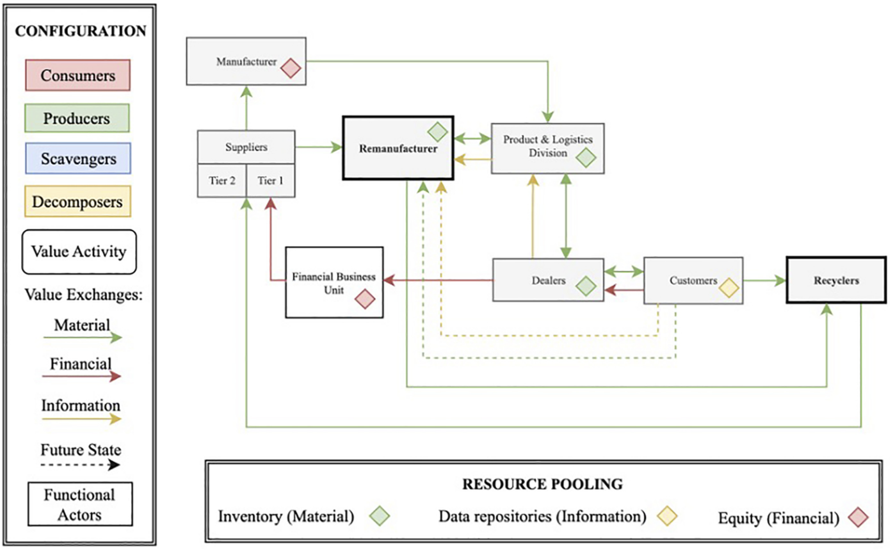

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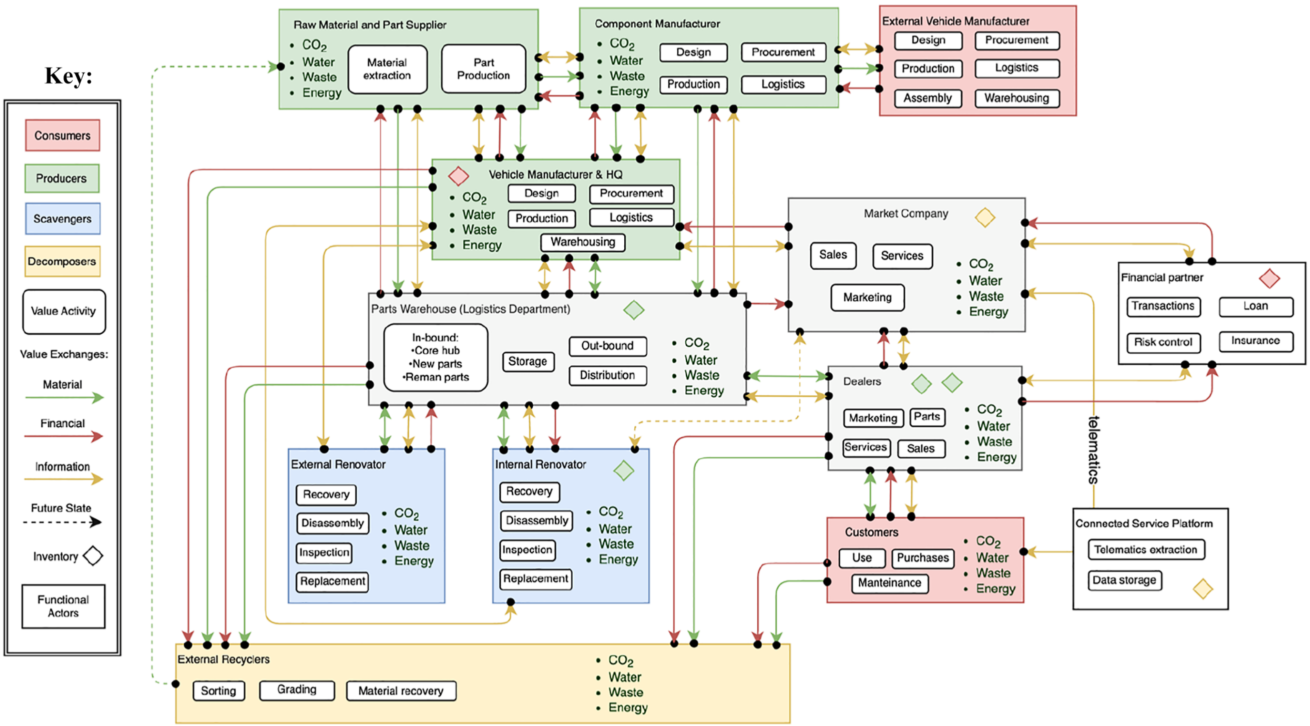
Figure 2. Data collection configuration and resource pooling framework

Findings

Resource pooling

The cross-case study analysis adopted a common mapping approach using the configuration and resource pooling framework in Figure 2 which captures the complexities of multi-actor cyclical flows. Its application is illustrated in Figure 3 which represents the European remanufacturing Case 4. This case was selected to exemplify the approach and the nature of the output because it displays existing resource pools and resource pooling opportunities. The outputs of the mapping approach for all cases are summarised in the cross-case analysis section in Table 2.

The utility of the approach is demonstrated by determining the location of available stock, the available material specifications, product usage data and the SN relationships in terms of power and interests . The analysis of circular ecosystem dynamics in terms of stock, data and value movements among stakeholders reveals stock accumulations, information holes and cash flow barriers. The approach is then used to highlight opportunities for digital interventions and intermediary involvement to fill these circularity gaps. Such analysis is shared with respondents to examine future state configuration options to scale the circular ecosystem. For instance, the example in Figure 3 illustrates opportunities to exploit telematics data to estimate more accurately the residual value of components at their end-of-life, thus informing remanufacturing forward-reverse flow management and product/network design decisions. In the current state, telematics data is utilised primarily for end-customer applications to increase service offerings during product usage; thus logistics, manufacturing and market company actors extract relevant trends and patterns manually from the datasets for end-of-life decisions. Therefore, the circular ecosystem map in Figure 3 reveals the potential for telematics data to be linked with corresponding product components and be integrated



Source(s): Authors' own creation

Figure 3. Configuration and resource pooling example application (Case 4: Automotive MNE Circular Ecosystem)

across the entire circular ecosystem to reach designers and renovators. Direct flows between the customer and remanufacturer, while possible, are currently routed via “third party dealers” as evidenced by the operations managers interviewed. In the future, information pooled via a digital platform could allow direct material flows from multiple tiers of customers for reprocessing. Furthermore, Figure 3 illustrates the resource, information and financial flows required to support such circular ecosystems, which in the case of the automotive MNE reveals information and material holes between customers and actors involved in the renovation process. Table 2 later extends the analysis to configuration, stakeholder and digital technology for all five case studies in tabular form.

Case analysis

Case 1 – Textile passport

The design and nature of apparel and textile products make the development of related circular economic models particularly challenging. This is because the majority of textile products are made of blended materials in multiple formats and colour variations, which are difficult to collect and sort in consistent volumes for scalable reselling and recycling operations. For instance, even if the product is 100% cotton it still likely contains some polyester thread. Existing circular operating and business models consist of repair and resell, typically managed by charities, independent shops or third parties on a small scale, and some degree of textile sorting and recycling, mainly mechanical leading to material downgrade. The sorting process currently relies on manual classification and separation subject to human interpretation and error, e.g. detailed inspection for product-brand verification required for reselling and separation in textile piles comprising different materials and colours conductive to recycling. Furthermore, the lack of visibility over product content is one of the greatest barriers to textile collection and sorting at scale. The case company in this research is among the first to implement a digital product passport on all of its garments, on millions of units. The product identity can be scanned by re-sellers to access original product information, such as photography, size charts and use history and as well as by the recycler to extract material content and chemicals. The information is either available on publicly accessible ledgers or released on request by the brand as a new revenue model. This is in line with the new measures enforced in Europe to regulate the apparel and textile industries such as extended producer responsibility, restrictions on production processes and regulations on labels to limit waste from fast fashion. Even though the case company is headquartered in the USA, its manufacturing and sales are spread globally. Textile manufacturing is primarily manual with skilled labour in Southeast Asia while textile reselling and recycling facilities are being set up in Europe resulting in geographical dispersion and multiple legislative contexts. Furthermore, legislation can hinder circular design choices due to inappropriate classification of circular products and consequently higher taxation import rates. One example is that of recycled cotton which counts as a synthetic with higher duty rates. This leads to a mixed material design for lowering the taxation costs of the overall product but also leads to more difficult end-of-life separation and recycling. See Figure A1 in the Appendix for the resource pooling map.

Case 2 – Battery passport

As demand for electric vehicles (EVs) grows so do concerns about the impending scarcity of lithium hindering net-zero aspirations. The battery passport regulation was mandated by the European Commission to minimise the harmful effects of batteries on the environment throughout their entire lifecycle by mandating the inclusion of an electronic record on every battery for all batteries larger than 2 kWh by 2027. A German-funded consortium of competing companies, solution providers and institutional bodies was formed to develop definitions, standards and data governance guidelines to ensure traceability along the entire value chain. The battery passport is governed by a federated EU central registry containing a list of every battery on the European market. It works as an Electronic Exchange System linked via a QR code that reroutes information requests to digital individual battery passports to extract decentralised data owned by vehicle original equipment manufacturers (OEMs). Each battery passport includes battery composition, responsible sourcing and carbon footprint, as well as recycled content. The battery passport can open the battery end-of-life market to third parties or enable the introduction of new data monetisation models. Nevertheless, the case study vehicle manufacturer has developed internalised secondary battery processing facilities, e.g. remanufacturing, repurposing and recycling operations on each major continent to capture the residual value of their own batteries. See Figure A2 in the Appendix for the resource pooling map.

Case 3 – US Remanufacturing

The case company has a primary global remanufacturing centre where parts, namely engines, injectors, hydraulics, etc. are returned from dealers worldwide. The globally centralised configuration is driven by tax and import restrictions on waste products in different countries. Dealers are charged the same price as for the corresponding new product for a remanufactured one (also referred to as a core). Only when the core is returned and inspected, can dealers request and receive the deposit, paid back as an incentivisation mechanism. The global distribution can result in a lengthy time, up to one year, for parts to arrive at the remanufacturing facility after being sent by the dealers. The advantage of this model is the availability of large amounts of stock which can be pooled for different remanufacturing products. In fact, after the parts are inspected, disassembled and cleaned with advanced automated salvaging technologies they lose their identity. This material pooling approach allows for flexible and efficient re-use of components throughout multiple cycles, e.g. engine cylinder heads can be re-bored to fit pistons up to three times larger. The high-value metal contained in components justifies the economics of this model. On average a remanufactured product contains 50–60% of remanufactured components while the remainder is replaced with new parts. Data analytics is used to deliver after-sales services, develop tailored additional offers for dealers and customers and optimise forward-reverse flow planning. See Figure A3 in the Appendix for the resource pooling map.

Case 4 – EU Remanufacturing

Remanufacturing operations for the case company are subdivided into four main divisions, one of which is trucks. The returned products all go through a central distribution centre to the central remanufacturing facility for inspection, assembly and testing. Employees across different divisions interact quite closely to expand the remanufacturing business with new solutions and service offerings. The remanufacturing process is similar to that of Case 3 where dealers send a box or pellet containing worn-out parts to the remanufacturing facility for inspection and reprocessing in order to claim back the core deposit that was charged at the time of sale. It takes approximately a week to a month for worn-out parts to arrive at the remanufacturing facility. Only 30% of remanufacturing is conducted in-house while the rest is managed via suppliers. At an assembly level, the ratio of remanufactured to new components is approximately half. Product identity is tracked throughout the remanufacturing operations to maintain separate components across multiple brands. In terms of digitalisation, there is a fleet management system built for end-users to track their own vehicles, enhance safety on the road and provide better uptime. The data gathered from the fleet management system is currently not exploited for growing the remanufacturing business. Instead, the case company leverages its loan-based financing to increase the lifecycle of the vehicles through predictive maintenance as it keeps control and ownership until full loan repayment is made. Remanufactured products provide customers with better uptime than repair and environmental benefits at a lower total cost of ownership for the same quality and warranty as new products. To increase the size of the remanufacturing business, the company intends to shift to fully servitised models to allow for better maintenance and end-of-life operations management with more localised interventions. See Figure 3 for the resource pooling map.

Case 5 – Circular Platform

The case company manufactures a wide range of products from low-value electronic components to customised high-value circuit breakers for commercial buildings that have a life span ranging from 10 to 30 years. A take-back platform was developed following a customer survey showing that the majority would be interested both in returning their used products and in buying refurbished ones. Customers can raise a take-back request for the used products to be collected by the case company and in exchange they receive a voucher for future purchases. All take-back products are transported to the take-back distribution centre where a distinction is made between energised and non-energised products. Energised products are refurbished or remanufactured at either the original manufacturer or the mother plant as they have the highest technical competencies and testing capabilities needed to guarantee quality and the warranty period without jeopardising the company's reputation. Non-energised products are tested and repackaged by strategic partners in order to minimise the carbon footprint from reverse logistics. Energised products are managed internally because they are dependent on the company's core expertise and testing equipment, requiring an investment of millions. For non-energised products this is not the case, but rather a matter of logistics efficiency. Take-back is incentivised by EU legislation on extended producer responsibility with a certain percentage of circularity often required to win bids. In line with legislation, the company aims to decouple material usage from business growth. Furthermore, across functions, they are rethinking the current business model as they would like to become more software-driven and co-innovate from product design, e.g. simplify material and product catalogues. The take-back platform can support business servitisation by providing knowledge and insights into customers' buying behaviour insights. See Figure A4 in the Appendix for the resource pooling map.

Cross-case analysis

The circular ecosystem maps allowed for extracting configuration and stakeholder dimensions and identifying critical resource pools used for circular operations. The findings of each case and the cross-case analysis are summarised in Table 2 based on interviews and mapping analysis with recurrent themes set out in italics. Recurrent themes were derived as part of second-order thematic observations (indicated in underlined text in Table 2). These second-order themes are network localisation, circular stock availability, functional/network integration, residual value capture, system-wide policy coherence and network-wide digital integration.

The cross-case analysis of configuration, stakeholder and digital technology attributes illustrates different types and levels of resource pooling, as summarised in Table 3. Distinct resource pooling patterns are identified, indicating a correlation between the level of resource pooling and the scalability of the circular ecosystem. For instance, in Case 2, the implementation of the industry-level battery passport is an example of information pooling enabling the scalability of circular operations. In contrast, in remanufacturing Cases 3 and 4, a material resource pooling configuration is deployed through an inventory management system that also supports scalability. Case 3, however, displays a centralised configuration managed internally compared with Case 4 which relies on external remanufacturers for approximately 70% of parts. A further archetype configuration is observed in Case 5, where the circular portal for take-back, together with the multi-life e-commerce platform, enables three types of resource pooling, namely material, information and financial. In fact, the combined resource pooling between primary and secondary production provides production planning flexibility with an increased potential for scalability.

Table 2. Cross-case analysis of framework dimensions – emerging themes

Case 1 – Textile passport	Case 2 – Battery passport	Case 3 – US Reman	Case 4 – EU Reman	Case 5 – Circular platform	2nd order themes
SN *structure:* geographical dispersion, production processes					
Globally distributed SNs with low-level manufacturing automation shifting to *regionalised* resell/recycling	Reconfiguration towards *localised SNs* with automated processing	Centralised international remanufacturing centre with advanced automated salvaging processes	*Regionalised internal* remanufacturing centre with and external providers, manual and automated salvaging processes	End-of-life intertwined with *local* primary production through centralised *regional* distribution centre	*Circular network localisation driven by manufacturing capabilities and short lead-times* Case 1,2,4,5
Product value structure: circular design, value/scale					
Low-value mass-produced *variable products* designed for durability due to mixed materials difficult to separate	Mid-value future commodities designed for *multi-stage end-of-life* decisions not commercial yet	Standardised mid-value products designed for *multi-stage parts salvaging*	Standardised mid-value products design for *ease of disassembly* and inspection	Ranging from commodities to high-value at low scale with manual end-of-life processes	*Circular processing constrained by stock availability at suitable volumes* Case 1,2,3,4
Governance: cross-functional circularity initiatives, level of SN integration					
Vertically integrated company requiring *industry-level integration*	Reconfiguration towards *vertically integrated* automotive and battery value chains	Low-level of cross-divisional integration, centralised remanufacturing SN	High-level of *cross-functional integration* for circularity, disintegrated SN	High level of *cross-functional and divisional integration*, decentralised remanufacturing SN	*Circular ecosystem dependent on functional and/or network integration* Case 1,2,4,5
Stakeholder interests: company circularity focus, intermediaries and customer drivers					
• *Least material fidelity loss* by leveraging data • Second-hand *product/brand authentication*	• Keep batteries in use for longer and address *raw material scarcity* • Accessibility to EVs services and end-of-life market	• Grow parts range for reman to increase business opportunities • *Cost savings* and *product identity retention*	• *Increase internal margin* and *part availability* • Lower costs, emissions and increase uptime	• Set the standard for green certifications • Motivated by *service offerings* and cost reduction	*Financial interest in residual value capture for long-term profitability* Case 1,2,3,4,5

(*continued*)

Case 1 – Textile passport	Case 2 – Battery passport	Case 3 – US Reman	Case 4 – EU Reman	Case 5 – Circular platform	2nd order themes
Stakeholder influence: legislation, data access, or product ownership					
Disincentivising taxes on circular materials and brands aim to keep control of data *hindering standardisation*	BP opening the end-of-life market, companies setting *internal* SN*s to keep control* via product ownership	*Taxation* on second-life *results in global shipping* for reman or data access loss with second-hand sales	*EU directive* incentivises circular operations as manufacturers are *responsible for end-of-life* products	Platform ecosystem *relies on customers providing data acces*s to benefit from service offerings	*Circular models need system-wide policy coherence for data access and tax/duty rates on circular products* Case 1,2,3,4,5
Digital technologies: architecture and purpose					
Standardised publicly accessible ledgers for proving items' authenticity, data controlled by the brand-owning company	Federated system linking information requests to decentralised battery electronic exchange systems for circularity	*Equipment management platform* for tracking usage, connecting with dealers and maintenance	*Fleet management system* for customers to optimise vehicle usage with telematics	*Remote cloud platform* collecting critical data from sensors to assist utilities and anticipate failure	*Lack of standards for network-wide digital integration for circular ops, platforms mainly customer focused* Case 1,3,4,5

Source(s): Authors' own creation

Table 3. Resource pooling configurations

Cases	Configuration characteristics	Stakeholder dimensions	Resource pools	Ecosystem governance	Ownership transfers
Category A – Information pooling (for resource recovery)					
Case 1: Textile passport	Globally distributed vertically integrated network	Brand-controlled data, end-of-life product loss	Single-brand information pool	Industry consortium level	4
Case 2: Battery passport (BP)	Shift toward localised vertically integrated network	Federated system for end-of-life management	Industry-wide information pool		
Category B – material and financial pooling (for remanufacturing)					
Case 3: Data-driven analytics	Centralised international remanufacturing operations	Economic drivers for circular operations	Centralised material pool	Dealer mediated	3
Case 4: Vehicle telematics data	Regionalised internal and external operations	Legislative drivers for circular operations	Internal material pool + external partners		
Category C – information, material and financial pooling (for resource optimisation)					
Case 5: Circular product portal	Intertwined primary and secondary operations	Service offering via customer incentivisation	E-platform multi-resource pool	Platform driven	2

Source(s): Authors' own creation

Three circular ecosystem archetypes emerge from the cases (see Table 3 and Figure 4): (1) information pooling for resource recovery enabled by digital product passports for material traceability (Cases 1 and 2), (2) material and financial pooling for remanufacturing exploiting data analytics and integration technologies for product condition and usage monitoring (Cases 3 and 4), as well as (3) material, information and financial pooling for resource optimisation through product connectivity via IoT architecture through digital platforms (Case 5).

The findings suggest possible evolution pathways for digitally enabled circular ecosystems. These may evolve from material passport pre-competitive institutional and industry collaborations to dealer-mediated network integration supported by analytics for take-back operations, towards platform ecosystems for optimising information, material and financial exchanges connecting competing and non-competing actors. The ecosystem governance of the different archetypes is influenced by the number of ownership transfers across different actors (see last column in Table 3). The ownership transfers are highest in Archetype A, which is driven by an industry consortium, followed by Archetype B which is managed at a network level via dealers and then by Archetype C which is led by a brand-owning platform.

The digitally enabled circular ecosystem archetypes displayed in Figure 4 depend on the deployment of their characterising resource pools to allow the cyclical flow of materials and products. The interrelationships between stakeholders and resource pooling models characterising each archetype are codified and described in the following bullet points:

(1) Archetype 1 is "an open ecosystem of free-flowing products and material that relies on information pooling". This is characterised by materials/products moving across multiple actors throughout their lifecycle. Hence, the ecosystem relies on a digital material or product passport (also referred to as an information pool) containing

relevant material/product data that ecosystem actors can retrieve and complement. Such material-product lifecycle information allows actors to determine the most appropriate circular channels for retaining the embedded value of materials and products at their highest form.

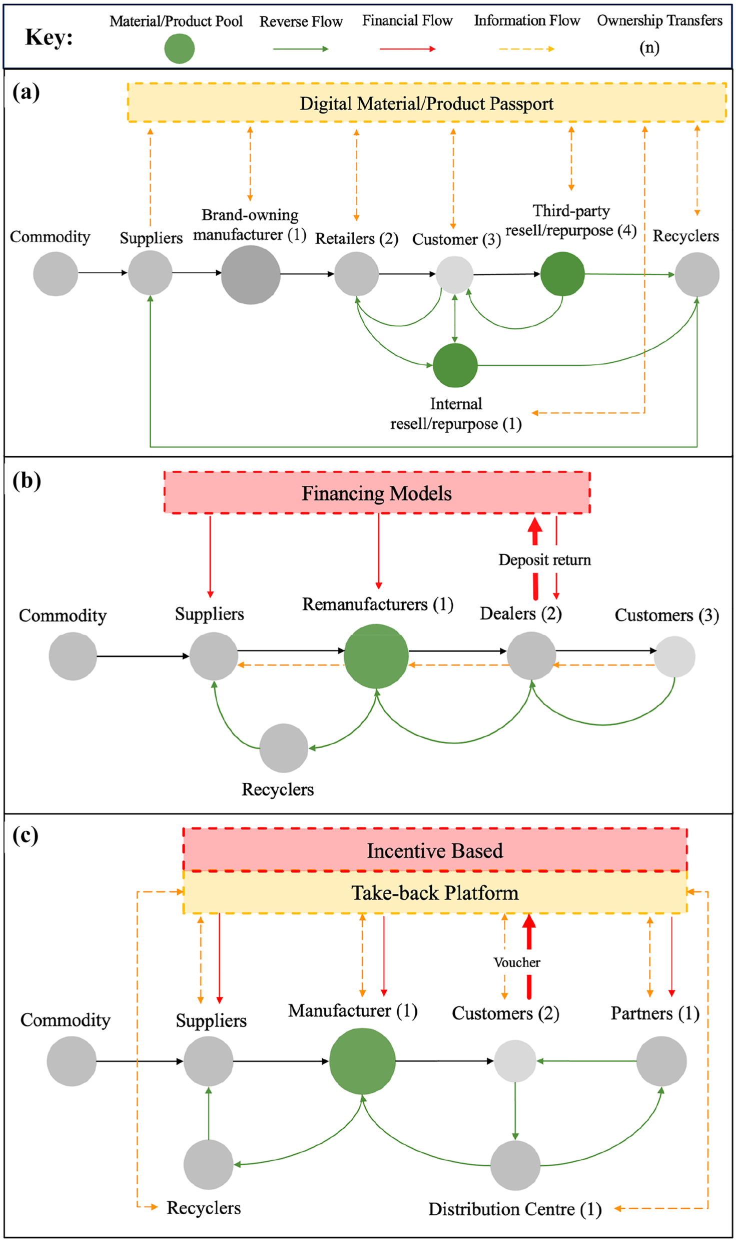
(2) Archetype 2 is “a triad network ecosystem where product returns are financially incentivised to pool capital and stock for remanufacturing operations”. It is characterised by close bilateral interactions between the remanufacturer-dealers and dealers-customers to ensure products are returned after their use for remanufacturing operations. The remanufacturer and dealers provide monetary incentives for product returns to maintain sufficient inventory levels and financial resources for reprocessing operations.

(3) Archetype 3 is a “circular platform ecosystem with the product manufacturer orchestrating resource exchanges between customers by pooling information, financial and material for circular operations”. It is characterised by the manufacturer facilitating resource circular exchanges between multiple customers using a re-commerce type platform and a circular distribution centre for product returns and resales. The take-back platform and circular distribution centre enable the efficient exchange of resources across multiple actors resulting in primary and secondary productions becoming intertwined.

Discussion and conclusions

The aim of this research was to investigate how digital technologies might enable circular ecosystems drawing on the theoretical lenses of SN configuration and resource pooling. The selected theoretical lenses provide a system perspective for the transition to circular business and operating models, which has so far had limited focus. Although configuration theory is well established in the strategic and SN management literature, it has not been featured in the study of circular SNs. In this research, we expand on SN configuration and related literature by focusing on material, information and financial flows which allow the study of SN coordination amongst multiple stakeholders (Eltantawy *et al.*, 2015). We hereby introduce resource pooling, which leverages resource flows, as an additional lens in support of configuration to uncover the availability of resources because the latter become valuable assets when aggregated. Resource netting and pooling approaches, traditionally used to optimise financial transactions among multiple stakeholders, have so far not been applied to improve material and product transfers among SN actors due to the linearity of the majority of extant SNs (Srai *et al.*, 2022). Nevertheless, the combination of resource pooling and configuration lenses supports the analysis of complex circular SNs through the visualisation of cyclical resource exchanges among ecosystem actors. In fact, the findings of the cross-case analysis reveal different types of pooling configurations and their related governance modalities, demonstrating the applicability of resource pooling as a critical lens supporting the design and scalability of circular ecosystems.

Managing resource pools is extremely challenging and relevant for the development of circular ecosystems that rely on the ability to quantify and locate available stock. This finding is particularly insightful in the manufacturing supply chain context and has parallels with considerations observed in the built environment, e.g. using digital technologies for visualising and forecasting construction material stock flows in urban environments (Tanikawa and Hashimoto, 2009; Wuyts *et al.*, 2022). Furthermore, new financial models that account for multiple resource transfers among actors need to be developed to financially sustain material exchange platforms and data repositories. By utilising the configuration and resource pooling maps for the visualisation of resource flows and pools, practitioners can identify “circularity holes” and develop suitable stakeholder engagement and digital intervention strategies to reconfigure their resource pooling models and increase the scale of circular operations.



Source(s): Authors' own creation

Figure 4. Circular ecosystem archetypes characterised by different configuration-governance modalities, (a) Information pooling (resource recovery), (b) Material and Financial pooling (remanufacturing) and (c) Information, Material and Financial pooling (resource optimisation)

Furthermore, the dynamics of resource pool availability/depletion are typically not considered in the development of circular SNs and can lead to circular business model disruption or failure. The visualisation of resource pools, demonstrated with practical cases in this research, enables resource management strategies at both the design level (e.g. configuration and resource pooling maps) and at the operational level (e.g. through appropriate monitoring/analytics and circular stock metrics). A progression of the current approach would involve modelling tools that can simulate resource shortfalls/surpluses and implications of the time lag between supply and demand in circular operating and business models. Thus, the resource pooling configuration maps lend themselves to system-dynamics analysis that can determine the factors that influence stock levels, whether in the form of material, financial, or information flows.

The results suggest several connections with related operations management fields. Firstly, circular SNs require alternative value capture modalities, e.g. service-based, which are influenced by product characteristics, internal collaborations as well as network and institutional settings (Kreye and Van Donk, 2021). Secondly, alternative configurations can be examined through social network analysis to understand governance dynamics (Marques and Manzanares, 2023). The latter focuses on the traditional network structure, whereas the opportunity to extend to the four dimensions of network configuration (Srai and Gregory, 2008), as we have undertaken in this paper, can lead to insights on the impact of alternative product architectures, production processes and perhaps, most importantly, geographic dispersion. Indeed, these configuration dimensions, in our circularity context, indicate connections between (1) product value structure which includes product characteristics (e.g. product design), (2) governance that also involves internal and network collaborations (e.g. cross-functional alignment) and (3) product and data ownership which may be influenced by institutional settings. This has implications for stakeholder analysis and calls for the inclusion of stakeholder theory in circular economic transitions. Finally, digital technologies and platforms emerge as critical concepts in circular operations research to manage the increased flow of information between SN actors.

Theoretical contributions and implications for practice

Firstly, this research introduces a new approach to understanding circular economy through the lenses of SN configuration (Srai and Gregory, 2008) and resource pooling, commonly used in financial management systems (Hofmann, 2007), to identify digital technology enablers of circular ecosystems.

Secondly, we identify three digitally enabled circular ecosystem archetypes: pre-competitive consortia-led information pooling for resource recovery, dealer-mediated material pooling for remanufacturing and platform-driven information, material, and financial pooling for resource optimisation. While not exhaustive, we uncover distinct resource pooling archetype configurations and related governance modalities characterising circular ecosystems through the codification of configurational, stakeholder and digital technology attributes across the case studies. The circular ecosystem archetypes with their associated resource pooling configuration and related governance modalities provide potential circular design rules for practitioners and/or policymakers to make informed decisions on digital technology investments and institutional interventions.

Thirdly, for each archetype, the maps capture resource exchanges and pooling models among network actors. This demonstrates a new approach to visualising and analysing complex circular SNs in their current state whilst still taking future projections into consideration. Furthermore, framing circular ecosystems in terms of resource pooling reveals opportunities for digital interventions, intermediary involvement and network reconfigurations that are required to enable scalability. The applicability of this framework to a range of different sectors proves its ability to provide insights into circular SN design and to inform digital transformation strategies for increasing the scalability of circular operations.

Researchers can utilise the resource pooling approach for comparative studies of circular SNs across industries. Practitioners can apply the mapping framework to observe their circular SN in a structured and clear format.

Fourthly, the framework lends itself to a staged process for practical implementation that consists of identifying: (1) actors and actor types, (2) material flows and stocking points, (3) information flows and data repositories, (4) estimated financial flows, (5) systems analysis on resource cumulation and depletion and (6) governance models to balance supply and demand as well as mitigate potential system imbalances.

Finally, this research introduces the notion of cyclical resource flow in a system where valuable stock is tracked, accumulated and reprocessed, analogous to financial stock transactions. As in financial systems, digital technologies are a critical enabler for these cyclical resource flows in a circular ecosystem. The resource pooling lens provides a new way of looking at circular SNs. It highlights the potential of designing new operating and business models where products and materials are considered valuable assets and, hence, circulate among stakeholders in the form of transactions.

Limitations

While the research is exploratory in nature, developing a new lens to understand circular ecosystems and drawing on extensive interview data from exemplar case companies, the authors recognise the identified archetypes are not exhaustive. There are significant opportunities in applying the approach to new contexts that may highlight new configuration arrangements and resource pooling strategies. Nevertheless, the theoretical contribution is the demonstration of the revelatory nature of the approach. The approach, thus far, has been used in advanced circular operations within multinational enterprises but needs to be tested in more early-stage contexts where operational scale is yet to develop.

Future research

Future research could investigate the relationships between other operations management constructs such as servititisation (Kreye and Van Donk, 2021), swift and even flow (Eltantawy *et al.*, 2015) and stakeholder network (McLoughlin and Meehan, 2021) theories in a circular economy context. Other research avenues could also involve quantitative analysis of the environmental and economic impact across different stages of the circular ecosystem in terms of net material flows (i.e. % of components returned, reused, recycled) and net financial transfers (i.e. % total deposit refunded). Similarly, a life cycle assessment could be conducted to account for additional emissions incurred for forward and reverse flows and for any potential rebound effects. Additional avenues for future research could include modelling supply and demand dynamics in circular models to reduce the lag between the time for end-of-life stock to return to the processing facility in order to meet the demand for remanufactured, repurposed or recycled products. Finally, the resource pooling analysis could be used to determine the implications of where stock is held, lost and recaptured to identify opportunities for increasing reverse flow and reprocessing material by exploring incentivisation mechanisms to balance bargaining power and equity among SN actors.

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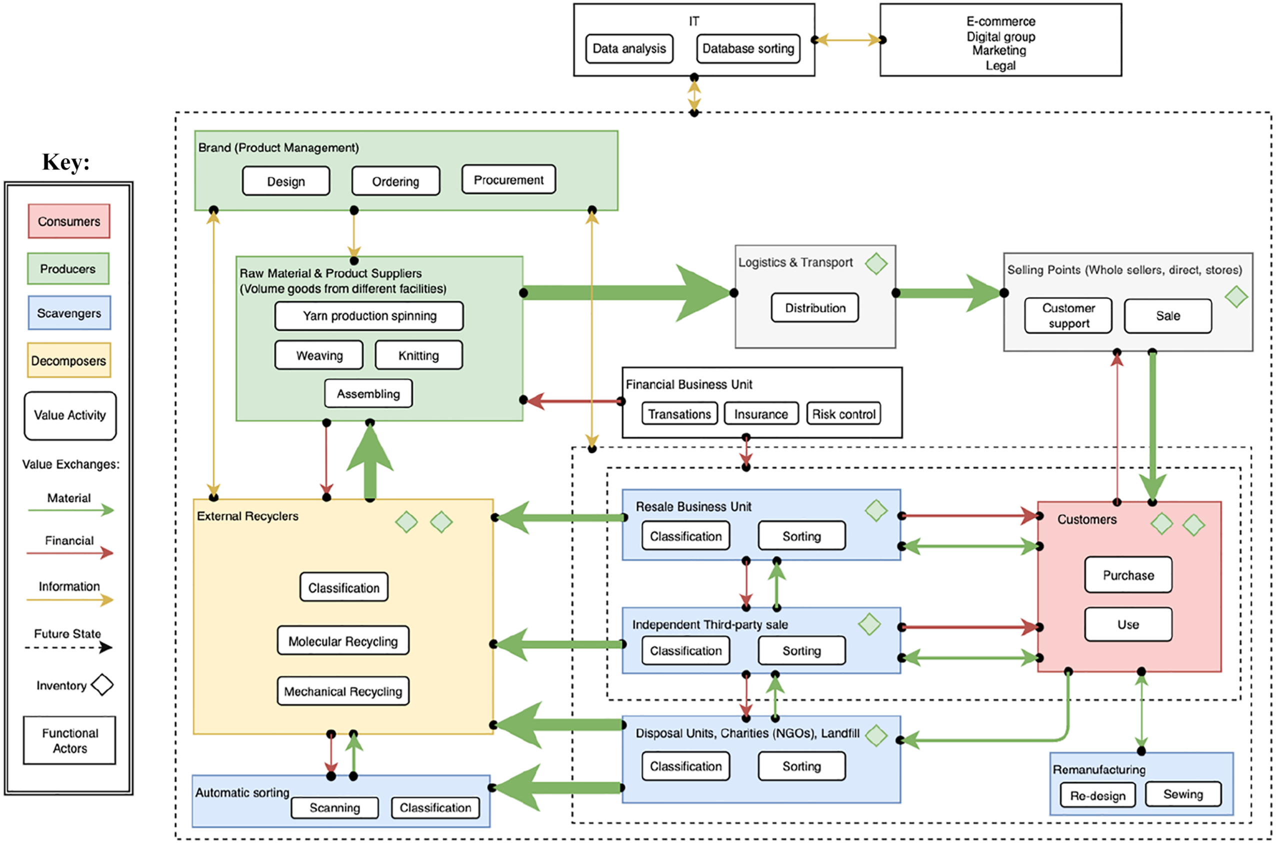

Source(s): Authors' own creation

Figure A1. Configuration and resource pooling Case 1: fashion MNE circular ecosystem

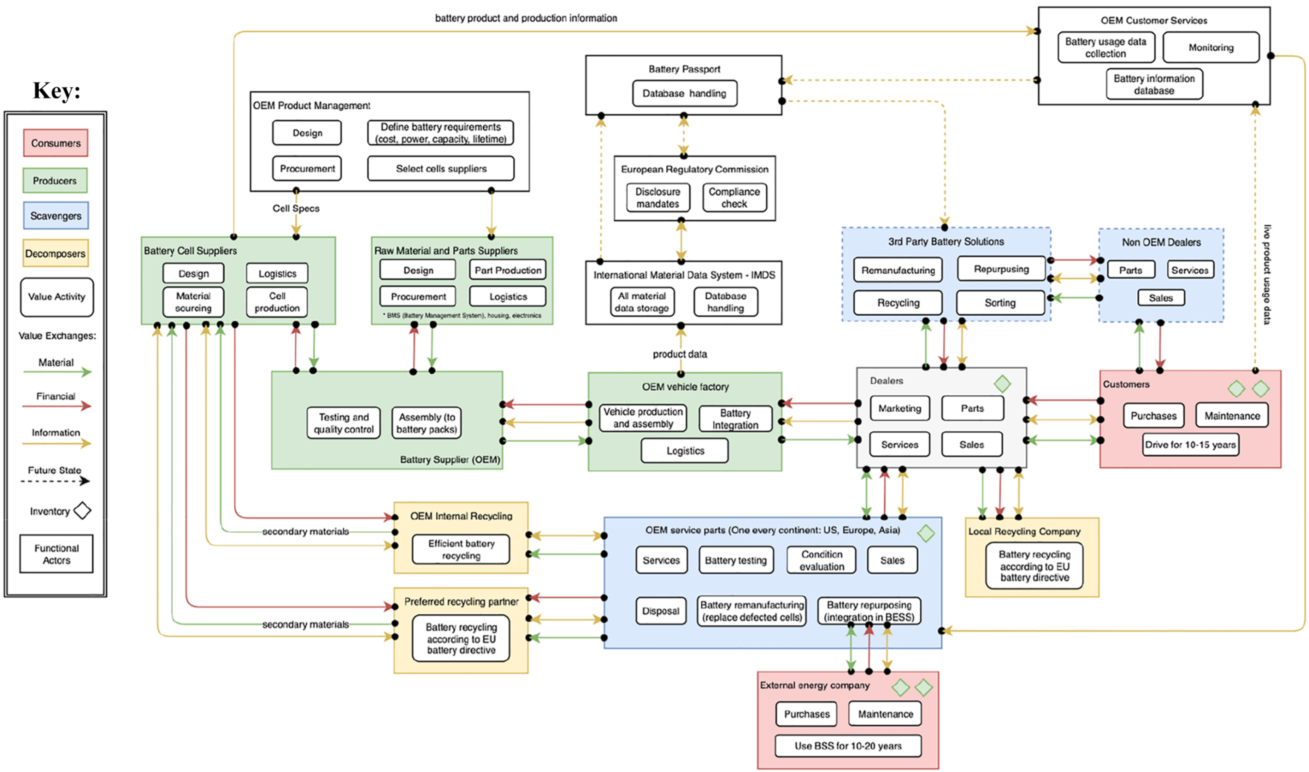

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Figure A2. Configuration and resource pooling Case 2: automotive EV MNE circular ecosystem

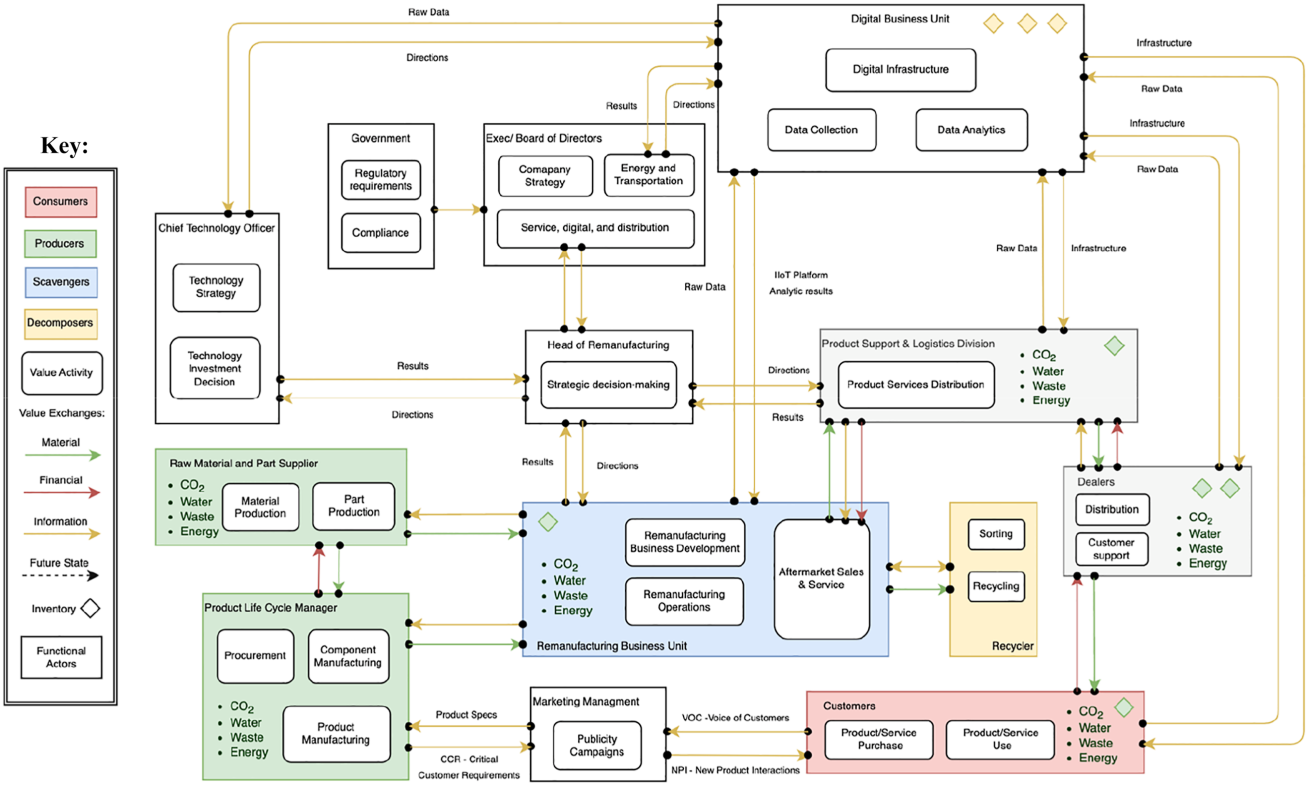

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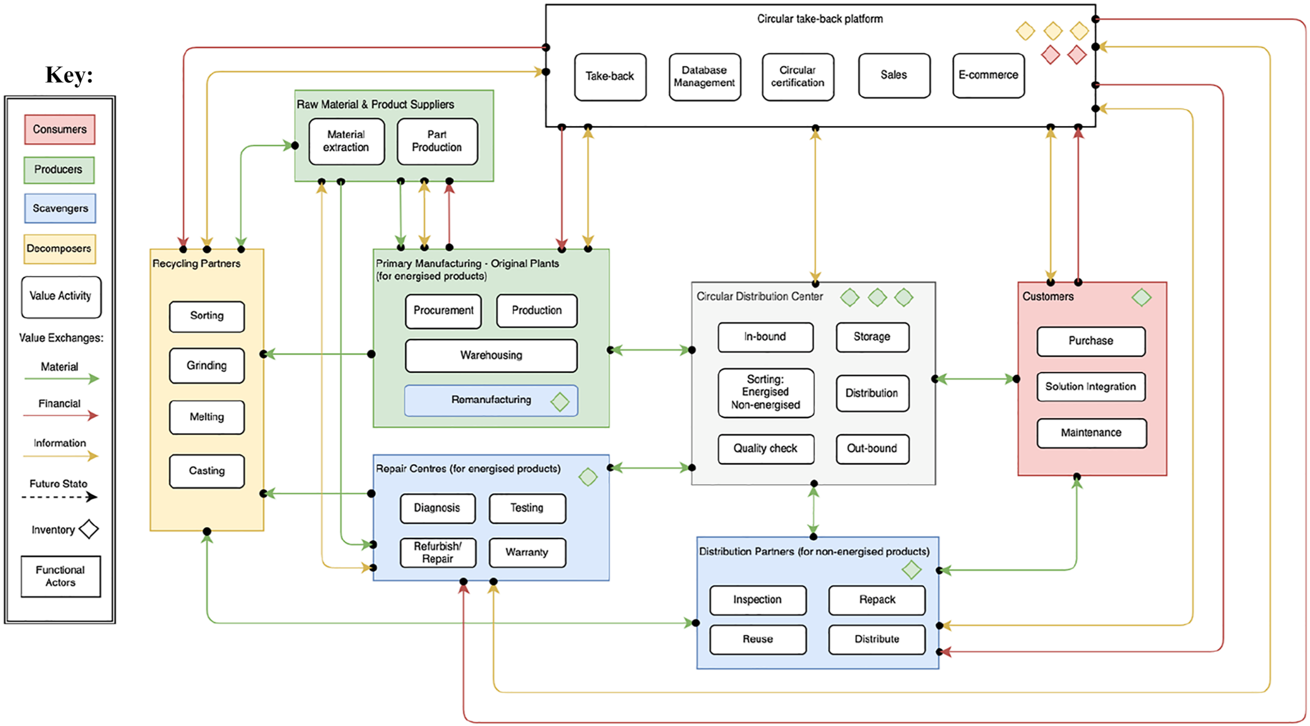
Figure A3. Configuration and resource pooling Case 3: construction machinery MNE circular ecosystem



Source(s): Authors' own creation

Figure A4. Configuration and resource pooling Case 5: automation MNE circular ecosystem