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Linking blockchain to circular economy – A view to global value chains

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Abstract: Circular Economy (CE) has taken a key role in discussion on innovation for sustainable economic growth. Reducing, Reusing, and Recycling – 3Rs – are widely acknowledged as primary principles and activities driving the transition. However, pursued goals are hard to reach if genuine implementation of these principles cannot be verified. For this verification, technological innovations such as Blockchain (BT) have shown promise, but it is not yet clear how CE and BT function together in a wider scale to promote innovative solutions. The global context of CE and BT challenge them both. Acknowledging this context, our study examines the potential of utilizing BT for CE in global value chains (GVC). Adopting a multiple-case study approach and examining global value chains of five multinational enterprises, we show how global CE-oriented value chains' features in terms of transparency, security, and dispersion, as well as control-orientation, location-specificity, and governance could be utilized with BT.

Keywords: Circular Economy; Blockchain technology; Global Value Chains; Sustainability; Industry 4.0.

1 Introduction

Circular economy (CE) mirrors how resources flow in natural systems (Ellen Mc Arthur Foundation, 2021) and aims to replace the "take-make-use-dispose" economic paradigm with a cyclical one based on the principles of Reducing, Recycling, and Reusing – the *3 Rs*

(European Parliament, 2015; Ghisellini, Cialani, and Ulgiati, 2016; Petit-Boix and Leipold, 2018; Zhijun and Nailing, 2007). The 3Rs inherently entail innovation. New business models and design reflecting these principles (Bocken, De Pauw, Bakker, and Van Der Grinten 2016; Confente, Scarpi, and Russo 2020), strategic alliances and collaborations via clusters or ecosystems (Hopkinson, Zils, M., Hawkins, P. and Roper, 2018), open innovation (Chaurasia, Kaul, Yadav, and Shukla 2020), and smart green platforms (Mathews, 2020) focus on sharing knowledge, raw materials, technology, and information in novel ways that promote CE. However, despite the achievements in the last decades (Petit-Boix & Leipold, 2018), obstacles persist.

Among one of the biggest challenges, continuous information exchange among stakeholders that would benefit CE and the related innovation is yet to be achieved. Paradoxically, in the age of Industry 4.0, with development of sophisticated systems such as internet of things, artificial intelligence, big data, cloud computing, cyber-physical systems, and smart manufacturing, the flow of information among actors is fragmented or even non-existent (Baldé, Forti, Gray, Kuehr, and Stegmann 2017). Challenges exist often due to acceptance and management tensions present in organizations that aim to demonstrate sustainability through open approaches, yet simultaneously pursue to secure their individual competitive advantages (van der Byl and Slawinski, 2015). Making things even more complex, the context for CE typically is global, which may add obscurity (see, e.g., Baldé et al., 2017). Goods are produced and distributed in global value chains (GVCs) through inter-connected phases across different locations, and with varied intangible elements (Buckley, Strange, Timmer, and de Vries, 2022). With regions in the world specializing in varying GVC stages (ibid.), CE is pursued in a complex system.

One suggested solution to better information exchange, that would enable long-term material circulation and the development of closed-loop models that employ waste from one operation as input for another (Stahel, 2016; Tate, Bals, Bals, and Foerstl, 2019), is employing Blockchain technology (BT) (Lopes de Sousa Jabbour, Jabbour, Godinho Filho, and Roubaud, 2018; Kouhizadeh, Zhu, and Sarkis, 2020). BT has been developed to manage a large amount of information in a decentralized way, from a distributed ledger with decentralized control (Swan, 2015). The technology is built under a secure and robust makeup, preventing tamper or alteration of the information while being openly accessible (to specific network of authorized members or more widely to the public; see Kouhizadeh et al., 2020).

These characteristics make BT useful for achieving transparency and permanency of transactions (Iansiti and Lakhani, 2017; Xu, Weber, and Staples, 2019) needed to generate cleaner and more resource-preserving collaborative solutions, as well as to unlock natural capital and empower communities (World Economic Forum, 2018). What also makes BT useful for innovating to respond CE challenges is that it readily shares some important elements with CE. Specifically, they both encompass the notions of collaboration, cooperation, common goals, interdependency, and interaction (Meadows, 2008; Reinsberg, 2021). These elements also match well with the notion that both BT and CE are inherently global phenomena (Brundtland, 1987; Murray, Skene, and Haynes, 2017; Nikolakis, John, and Krishnan, 2018; Yli-Huumo, Ko, Choi, Park, and Smolander, 2016).

However, BT may not be directly applicable to address the acceptance and management tensions present in CE, and there are numerous obstacles to adopting BT (Mougayar, 2016) – especially with globally varying conditions such as regulation (Yano, Dai, Masuda, and Kishimoto, 2020). Therefore, there is a continuing need to examine the interplay between BT and CE (see, e.g., Geissdoerfer, Savaget, Bocken, and Hultink, 2017; Kouhizadeh et al., 2020). A systematic literature review by Böckel, Nuzum, and Weissbrod (2021, 525) states, "closer examination of possible benefits and challenges of blockchain technologies for the circular economy with its links to sustainable development is crucial," particularly from a systemic perspective (Kumar, Singh, and Kumar, V., 2021): In modern supply chains, global parties, multiple layers, and various sectoral entities are present (Buckley et al., 2022), and CE supply networks are widely regarded as complex adaptive systems (Braz and de Mello, 2022).

Against this background, we argue that the interplay of CE and BT, and how firms approach it, can be understood by analysing Global Value Chains (GVC). GVC perspective focuses on the entire set of activities that constitute the value chain (Benito, et al., 2019), thereby capturing the concepts of interdependency, trust, and control among actors instead of merely viewing the individual or isolated actions in international markets. Likewise, the holistic features of GVC align with BT capabilities like decentralization, transparency, peer to peer (P2P) verification, and immutability (e.g., Böckel et al., 2021), and connect to the pressing issues in the CE such as inaccurate information, fragmented material traceability, vague metrics, and risk of greenwashing or cherry-picking (Geng, Fu, Sarkis, and Xue, 2012). Therefore, the logic of GVC can be considered to match and connect CE and BT.

In this study, we address BT as a source of innovative approaches for CE by looking into existing theorizing and examining empirically how multinational firms manage and perceive their GVC regarding benefits and challenges accruing from the interplay of BT and CE. By doing this, we aim to answer the research question of *how features of a firm's global value chain connect to the perceived opportunities and challenges brought by the interaction of blockchain and circular economy and the related innovation.* We adopt system thinking view as we study multinational enterprises (MNEs) following the CE logic and investigate those elements that reside – based on existing literature – in the common ground between CE and BT. A look to existing theoretical considerations and a multiple case study among CE MNEs allow advancing theorizing on the interplay of CE and BT.

2 Theoretical background

The Circular Economy – Goals and key notions

Circular Economy (CE) provides a new perspective that aims to restructure enterprises, society, and economic development (European Commission (EC), 2015) arising from the influence and evolution of four major fields: Performance economy, that proposes substituting manpower for energy (Stahel, W., 2010); Biomimicry, which aims to emulate natural systems (Beynus, 1997); Cradle-to-cradle (C2C) design technique preferring eco-effectiveness over eco-efficiency (McDonough and Braungart, 2010); and Systems thinking, which entails a holistic approach that encourages collaboration, cooperation, and coordination of players (Meadows, 2008). The concept of CE implies considering both environmental and economic benefits simultaneously (EC, 2015) and proposes new ways to generate value (MacArthur, 2013).

Two main frameworks explicating the transition in practice and theory are the principle of 3Rs – Reduce, Reuse, and Recycle – and the ReSolve framework, a more detailed approach introduced by the Ellen Mac Arthur Foundation. The ReSolve framework encompasses a set of six actions – Regenerate, Share, Optimize, Loop, Virtualize, Exchange – that emerge from three principles: control limited stocks and balance renewable resource flows; optimize resource yields by cycling products, components, and materials; and foster system effectiveness.

The 3Rs, as a holistic perspective, implicitly includes some of the actions suggested in ReSolve. 3Rs capture more concrete and detectable actions to close loops along the process. For instance, the *Reduce* principle refers to minimizing the use of materials, energy, and waste generated in the system by increasing efficiency in production and consumption through adopting new technologies, simplifying packaging, and using more power-efficient appliances, for example (Zhijun and Nailing, 2007). This principle is broken-down in the ReSolve framework as the dimensions of *Virtualize* and *Optimize*. The *Reuse* principle states that "products or components that are not waste are used again for the same purpose for which they were conceived" (Directive, E. C. 2008., p. 10) which can be linked to the dimensions of *Loop* and *Share* from the ReSolve sphere. The *Recycle* principle is defined as "any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes" (The EP and the Council of the EU, 2008, 10), which resembles the *Exchange* and *Loop* actions.

In this study, we use the more holistic 3Rs principle to look past business model innovation (more typically approached with the ReSolve framework; see, e.g., Lewandowski, 2016). By doing this, we aim to tap into the innovative ways to address the obstacles found to deter CE implementation.

Hindrances of CE implementation

There are several obstacles to the CE, many of which are interconnected – demonstrating CE complexity with multiple dimensions and domains (Ritzén and Sandström, 2017). Ritzén and Sandström (2017) classify the obstacles into five categories: Financial (inability to measure the financial benefits of CE); structural (lack of information exchange, ambiguous responsibility distribution); operational (supply chain management); attitudinal (perception of sustainability, risk aversion), and technical (integration in production processes). Similarly, Kirchherr, Reike, and Hekkert, (2017) note that the most prevalent barriers are presented in the spheres of cultural, regulatory, market, and technological fields. Measuring the impact of the CE has also proven difficult with missing social indicators or absolute material/energy reduction metrics. Absence of regulated data gathering methods lead to reporting being voluntary and possibly used for diverse purposes, unreliable or inaccurate data, problematic monitoring and auditing, and processes that can result in *cherry-picking* to showcase only successes (Geng, et. al., 2012).

According to de Sousa Jabbour et al. (2018), a lack of knowledge on product life cycles, and a scarcity of wide implementation of current technologies for cleaner production have hampered the spread of CE principles. Challenges to CE development in the context of Industry 4.0 stem from shortage of trained personnel, inefficient regulations-controls, ineffective performance framework, and short-term corporate goals burden CE development (Kumar et al. 2021). Furthermore, corporations are often unwilling to adopt ambitious goals with uncertainty around expenditures, return on investment, and execution timeframes (Su et al. 2013; Geng and Doberstein 2008). Nonetheless, with the proliferation of emerging technologies form Industry 4.0, it may now be possible to address such issues more effectively.

Blockchain technology assisting Circular economy

While Blockchain initially emerged in a different environment than the CE, and while they have evolved in separation, BT and CE have recently become connected (Böckel, 2020; Casino, Dasaklis, and Patsakis, 2019). A notion of a transparent, uninfluenced, decentralized, and open network emerging in 2008 with the invention of Bitcoin has expanded to various fields (see Cai, 2018; Cole, Stevenson, and Aitken, 2019; Esmaeilian, Sarkis, Lewis, and Behdad, 2020; Hawlitschek, Notheisen, and Teubner, 2018; Nandi, Sarkis, Hervani, and Helms, 2020; 2021; Swan, 2015; Saberi, Kouhizadeh, Sarkis, and Shen, 2019; Zhang, Zhong, Farooque, Kang, and Venkatesh, 2020). BT has been acknowledged not only as a general-purpose technology, but also an institutional one that can provide a platform for a new method of economic coordination and governance (Davidson, De Filippi, and Potts, 2018). Although there is no single definition of Blockchain identified in research (Pilkington, 2016), it can be described as *"A distributed database organized as a list of ordered blocks, where the committed blocks are immutable"* (Casino, et al., 2019). A distributed ledger (as a new way to record data) with decentralized control (with recordings verified by other parties in the network), transparency (necessitating that only accurate information becomes part of the blockchain), and strong construction (with every block being interconnected through complex mathematical functions) prevent information tampering or manipulation. Further benefits are reached when automatization optimizes processes and lowers the transaction costs.

Over its development from BT 1.0 (beginnings of cryptocurrency mining) to BT 2.0 (with smart contracts, i.e., self-executing actions to automatize transactions) and BT 3.0 (with development of decentralized applications), Blockchain has built on collaborative character (Upadhyay, Mukhuty, Kumar, abd Kazancoglu, 2021; Swan, 2015). The information stored on the blockchain may be open to the public and accessible to anybody (Iansiti and Lakhani, 2017; Xu et al., 2019), but not in uncontrolled manner: Each block must include a proof-of-work that is confirmed by other nodes on the network, which guides the cooperative and competitive forces across the network (see Narayan and Tidstrom, 2020). Unlike other technologies, BT features peer-to-peer connection, making it highly secure and verifiable. All the actors in the network have access to the same records (Iansiti and Lakhani, 2017; Moll and Yigitbasioglu, 2019), and once a transaction is updated and authenticated by the network's necessary nodes or key parties, it is irreversible and cannot be overwritten or re-sequenced (Upadhyay et al., 2021). These features are expected to make BT valuable and useful for CE (see, e.g., Böckel et al., 2020; Chidepatil, Bindra, Kulkarni, Qazi, Kshirsagar, and Sankaran, 2020).

Importantly, the creation of a shared and collaborative data setup on the Blockchain can enable the circular sourcing of renewable inputs, improve resource efficiency, and aid in material recovery and waste reduction by tracking flows across multiple actors (Tate, et al., 2019), thereby tapping directly into the 3Rs. While being innovative in itself, BT may be found advantageous in generating ground-breaking solutions such as new ways to reduce the carbon footprint or utilizing by-products, or in terms of allowing firms to connect with others in global value chains (GVC) in different ways. Digital networks enable distributing information about materials and supply chains more transparently, and blockchain technology can improve monitoring, and help to standardize metrics and expose illegal or unethical trading activities (Upadhyay et al., 2021; Herweijer, Combes, Johnson, McCargow, Bhardwaj, Jackson, and Ramchandani, 2018). The interplay of BT and CE is not straightforward, however. BT may not provide a solution for all areas of CE (e.g., sustainable design or optimizing product usage) (Herweijer et al. 2018), and the global context where BT and CE interact influences their interplay –not always favourably (Yano et al., 2020).

Operating in the global context – A look at the global value chains

Benito et al. (2019) point to two main aspects that distinguish global value chain (GVC) theory from previous internationalization or entry modes theories. The first one is the level of analysis. GVC shifts attention from the individual activities performed in foreign countries to a systemic approach that focuses on the entire set of activities that the value chains encompass. Here the interdependency among individual governance modes is more evident. The second aspect is trust as a complementary – and not substitute – to GVC coordination mechanisms. With trust complementing formal contracts, MNEs might promote more cooperative and long-term exchange (Benito et al., 2019; Poppo and Zenger, 2002).

These features make GVC perspective useful for understanding what the global context may mean for the interplay of CE and BT. BT infrastructure might promote GVC configuration and therefore benefit CE activities in the global scale. A contemporary GVC can be considered as a complex governance setting that mixes, in a single structure, the use of multiple governance types for various finely sliced and geographically dispersed parts of the value chain (Benito et al., 2019; Buckley et al., 2020; Kano, 2017). This indicates that reduction, recycling, and reuse can emerge in different locations and that the inputs for and outputs from these processes can be connected through BT. At the same time, a GVC is “inherently unstable and transient” (Denicolai, Strange, and Zucchella, 2015, p. 343) meaning that it accepts that both the actors’ interdependence and the power dynamics are continuously varying (Strange, 2011). This occurs, for example, when a company progresses from being a material or component supplier to a key production intermediary. Adaptability, relational co-dependency, and co-evolution – contributing to new forms of organizing such as the decentralized collaborative organization (Davidson et al., 2018) – resonate with both BT and CE requiring systemic perspectives (see Capra, 1982; Meadows 2008), and the integration of activities to achieve greater goals. Accordingly, looking at CE and BT interplay through GVC lens has the potential to explicate both the advantages and challenges emerging in this interaction, and point toward solutions to address the problematic aspects.

The GVC lens also responds to the calls for more examination (see, e.g., the literature review by Böckel et al., 2021). Considering that current literature positions BT as likely useful in the CE context, it is not surprising that studies have so far investigated the interplay of the two fields from the point of view of firms utilizing BT. The applicability to CE context and for promoting sustainability has been rather theoretical (Böckel et al. 2021; Nikolakis et al., 2018). Moreover, while current theory acknowledges the adoption of BT by firms and connects it with CE principles to find out its potential contributions towards the circular transition (Kouhizadeh, et al., 2020), also in global value chains (Nikolakis et al., 2018), the acquired insights tend to be limited to individual cases. There still is a scarcity of empirical data from the point of view of firms that are innovating along the CE logic and operating in GVC. The move of firms toward the CE or adoption of BT is a complex issue especially in international settings where value chains have multiple tiers (Nikolakis et al., 2018). Under the influence of cultural, political, regulatory, and other such differences present in GVC and networks, the functioning of the system is dependent on a variety of factors. To respond to the need for more research, we next examine empirically how features of a firm's global value chain connect to the perceived opportunities and challenges brought by the interaction of blockchain and circular economy and the related innovation.

3 Empirical examination

Data collection – Multiple-case study in stainless steel industry

We study the interplay between BT and CE empirically by adopting a multiple case study method (Eisenhardt and Graebner, 2007; Pauwels and Matthyssens, 2004) and examining multinational enterprises (MNEs) that follow the CE logic under the 3Rs principle. To uncover the potential of BT from the point of view of CE firms, we inquire about the GVC and, following earlier studies' lead (e.g., Upadhyay et al., 2021; Böckel et al., 2021), look into the known features of blockchain technologies in promoting innovative solutions.

For data collection, we narrowed down our selection to the companies in the stainless-steel value chain: On the one hand, the stainless-steel manufacturing process encompasses various steps with diverse players in dispersed locations, making their interaction a complex issue with concepts of cooperation, transparency, and trust (as theoretically established factors in the cross-section of CE and BT) playing a fundamental role. On the other hand, the steel industry is currently one of the highest Co2 emitters, with a total of 7% of all emissions globally (IEA, 2022). So, the implementation of CE in the sector has a significant impact, for example, when reducing the need to extract primary resources such as chromium or nickel from mines. Likewise, closing loops in the manufacturing process is highly feasible as different by-products are created along the process, fostering both the optimization of materials, and the cross-industrial collaboration opportunities. Therefore, the 3Rs are inherently present in the industry.

We collected the empirical materials by conducting semi-structured interviews with relevant decision makers in the firms and by retrieving their corporate sustainability annual reports, as well as public materials available on the topics of CE. Two global leaders in the production of stainless-steel were investigated. In addition, three customers of steel were analyzed, all with different applications: environment building, consumer products, and automobile industry. We collected altogether 621 pages of data, including 7 interviews (35-55 minutes each) that were coded and classified under our main topics of interest (i.e., CE, BT, GVC). Table 1 provides an overview of the selected case organizations.

Table 1 Case summary – Stainless-steel Global Value Chain firms

Case MNE	*Role in the Value chain.*	*Location*	*Revenue (2021, M EUR).*	*Employees (2021)*
M1	Steel Manufacturer	Finland	7,709	9,096
M2	Steel Manufacturer	Sweden	9,243	3,922
C3	Steel consumer. Application in the building environment.	Finland	10,514	+ 60,000
C4	Steel consumer. Application in customer goods.	Finland	1,254	6,690

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C5	Steel consumer. application in the automotive industry.	Sweden	35,809	95,850

Source: Own construction, data from interviews, sustainability reports, annual reports, corporate web posts.

We started our analysis by investigating the CE features and GVCs in the industry. Figure 1 below depicts the stainless-steel value chain as constructed from the data. Materials enter the manufacturing process via two routes: the primary route and the circular route. The first involves the extraction of raw metals from mines; it is used when recyclable materials (i.e., scrap) are unavailable. The circular route, on the other hand, involves scrap collectors and processors. Collectors obtain used material from various sources and sell it to processors who organize the scrap mixtures, sort it into different types, and sell it to steel plants (to M1 and M2).

In some cases, the manufacturers own mines and scrap-processing facilities. Case firms M1 and M2 operate their own mines in Sweden and Finland, respectively, but also obtain materials from international suppliers. The materials are then melted and mixed until the final product is completed. It is then sold to customers who transform it and incorporate it into their own applications before selling it to steel users (see C3, C4, C5). The value chain encompasses both national and international actors in every step of the process, making it highly complex with constant challenges that might slowdown circularity.

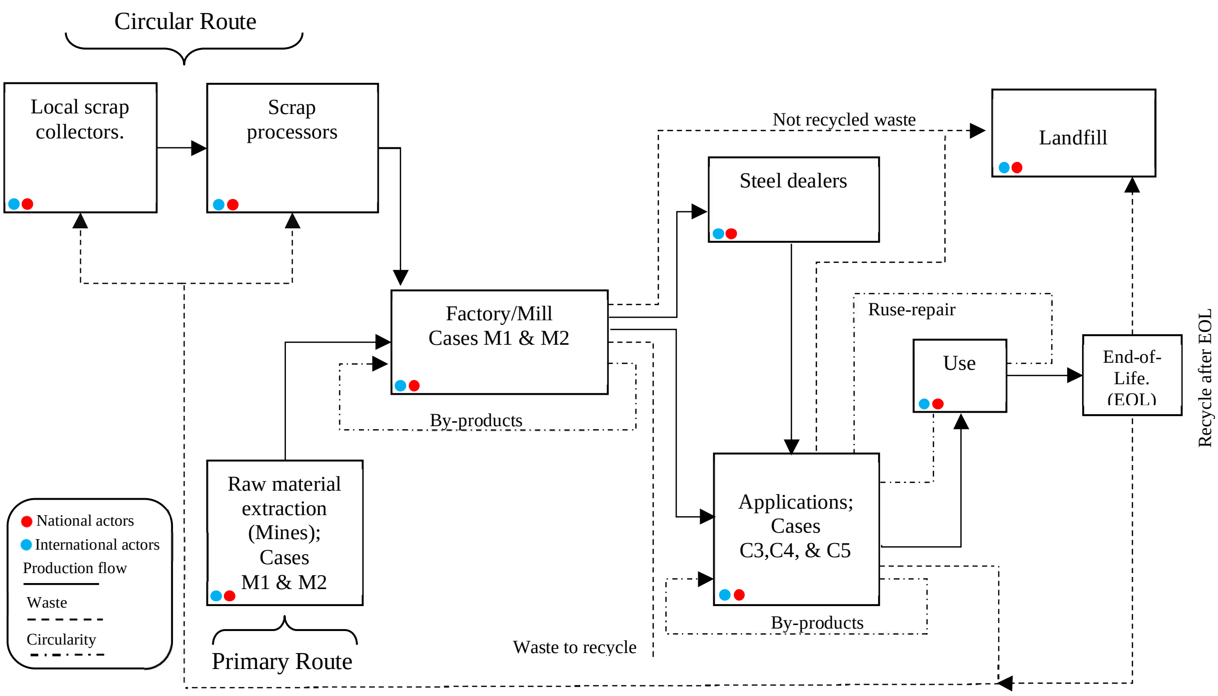

Figure 1. Stainless steel Global Value Chain and circularity.

The analysis suggests that CE principles are present at any stage of the manufacturing process. Stainless-steel is a long-lasting material and is fully recyclable at the end of its life

Table 2 CE and BT in the case MNEs.

Cases	*CE actions*	*Reduce*	*Reuse*	*Recycle*	*Hindrances in the CE adoption*	*BT capability*
M1	Reduced CO2 emissions intensity	✓			Supplier´s false information.	Transparency
	Reuse of acids and components in the production process.		✓		Shortage of scrap	Decentralization
	90% of recycle content	✓		✓	Logistical challenges due. GVC under pressure	Decentralization
	Use of Slag as by-products, By-product use rate 78%.	✓	✓	✓	Cyber security risks	Security; anti-tamper; immutable
					Risk related to price and availability of raw materials and supplies	Automatization of Transaction. Availability can be tackled by decentralization
					No communication with competitors	Security of the Information; Single ledger.
M2	The firm aims to reduce Sweden's CO2 emissions by 10% and Finland's by 7%.	✓			Unable to monitor all the suppliers, they monitor the high-risk areas instead	Security; transparency; self-Verification
	Goal to be the world's first fossil-free steel, with no carbon footprint in the value chain	✓	✓	✓	Some goals to reduce landfilled waste are not economically feasible	Decentralization and automatization of transaction
	More durable products with less weight	✓			Complexity of actors in the GVC	Standardization of information; transparency
	Optimizing the value of our by-products, scrap, and waste, with a focus on sustainability and value creation.	✓	✓	✓	Availability of scrap due to increasing demand of recycled products	Decentralization
C3	In 2019 it reduced 12% GHG emissions.	✓			Lack of standardization on sustainable goals within the Value chain	Transparency security
	Goal to become climate-neutral by 2030.	✓	✓	✓	Dependence of 35% of sales in a single market	Decentralization and transparency
	Goal to become the partner of smart and sustainable city development.	✓	✓	✓	Logistic complexity to offer maintenance services.	Security of the information and automatization of transactions; Permanency of the information
	Design of durable products that can be modularly upgraded	✓	✓	✓		

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	Suppliers' sustainability assessment	✓	✓	✓	No communicating with competitors	Information shared in a single ledger. Transparent, secure; preserves confidentiality
					Some sustainable information from suppliers based on trust.	Verification; Security; Transparency
C4	Goal of over 50% of net sales from CE by 2030.	✓	✓	✓	Challenges on global supply chains as well as raw material and energy price inflation	Decentralization
	Recycled products sales grew 78% in 2021.			✓	High logistics costs	Automatization of transactions
					Material and commodities availability challenges	Safe information and decentralization
	Goal to zero waste landfill by 2030.	✓	✓	✓	Confidentiality constrains.	Secure information exchange without diminishing confidentiality
	By-products made from waste.	✓				
	Set science-based targets	✓	✓	✓		
C5	Aim; 35% electric vehicles sales by 2030.	✓			To align all the actors in the value chain to the goal of net zero emission goal.	Transparency; Security ; Verification
	Goal to become 100% fossil-free.	✓			Difficulties to get suppliers information due to the GVC dispersion.	Security; Standardization of info.
	Net zero emissions from operation and supply chain by 2050	✓			Lack of extensive data of products lifecycle	Security; Permanency of information; Verification.
	Increase material efficiency and reduce energy use	✓	✓	✓	Challenges in by shortage in the supply chain.	Decentralization
	Offering service, maintenance/ repair to increase the product´s utilization rate	✓			Lack of broadly accepted standards of new technologies and usage of resources	Decentralization Single ledger; Transparency
	Considering sustainability from the design phase. (aerodynamics, and energy)	✓				
	Collaborating with the city authorities to reuse waste.	✓	✓	✓		

Source: Own construction, data from interviews, sustainability reports, annual reports, corporate web posts.

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However, the within case analysis (Eisenhardt, 1989) indicates the firms encounter several obstacles to a comprehensive CE implementation. Table 2 shows the current CE actions in the case firms. It also shows which 3R principles they address, as well as the challenges encountered. As the hindrances affect the principles indistinctly, they are not classified into any specific sphere. Moreover, we connected the CE challenges with BT capabilities that might address the issue in the same Table. The subsequent cross-case analysis then showed the features of GVC that connect to innovating in the intersection of CE and BT.

3.2 Findings

Our analysis suggests, first, that *transparency* plays an important role in CE GVCs. For example, the representative of M1 notes "W*e found out that one of our suppliers in Brazil was on 'red list'; they were giving us false information on their sustainability plans and we did not know until it was public."* A similar issue on transparency emerged in M2 statement: *"Most of our transparency is based on trust, what we see is what we get. We had a bad experience with a coal supplier in Colombia… we asked about health and safety in their coal mines, everything seemed ok. but what we didn't know is that they showed us only one mine and they had many others, and the conditions were not the same.* The lack of transparency may result in a final product containing questionable components, endangering not only the health of end users, but also stakeholders throughout the value chain, and impeding the implementation of the 3Rs, particularly recycling and reuse. Moreover, transparency is needed for novel approaches: *"It is absolutely crucial…. We are prioritizing sustainability in our operations...in the future, our customers will measure exactly what we measure here (at the plants), so we are trying to be as transparent as possible, false information sooner or later will be exposed."* (C5). Transparency is a key component for companies that implement innovative ways to verify the sustainable aspects of their products, and BT can provide such a setting.

Second, the empirical evidence suggests that there is a demand for *security* in GVCs when CE is used. Two companies (M1 and C3) express their inability to communicate with their competitors. Due to earlier issues involving unfair competition and confidentiality, and since M2 operates in the same industry, such limitations have an impact on potential collaboration opportunities. M1 respondent noted: "*For us is not so hard to talk to companies from other industries, but when it comes to partnering with our competitors, is basically no possible. We faced issues in the past, and we are forbidden to talk with competitors. which is a problem."* C3 representative stated: "*Ten years ago, companies exchanged too much information like agreeing market shares and so on, so the collaboration is [now] very strict. We are trying to exchange as less information as possible to avoid issues"*. BT can provide a secure environment for information sharing by safeguarding sensitive or confidential information, reducing the risk of forming ambiguous alliances, and improving the conditions for cross- and within-industry collaborations.

The inherent *dispersion* is the third main feature of GVCs that according to our data play a role in determining BT use for CE. The respondent from case M1 refers to this*: "We have raw materials suppliers out there in the world about 180 overall"*; *"we also have a global value chain with different regulations"; "we have steel across the world".* Such dispersion represents an extensive and complex monitoring endeavor. The interviewee from M2 said: *"we have thousands of suppliers, and we can't monitor all of them so we*

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monitor the high risk areas". When it comes to CE adoption, BT through a single reporting ledger accessible and verifiable by all the actors in the dispersed GVC may help.

Fourth, *control-orientation* emerges as a central GVC feature. In GVCs, it seems important, who performs different activities. The control over suppliers goes up to tier 1 and tier 2 at the most, leaving actors and activities out of the verification scope. While this also connects to controlling the resources, our empirical materials suggest that control over tasks allocation is relevant for ensuring CE principles genuinely executed while generating sustainable innovation. M1 describes this: *"It would be nice to get materials back from our customers directly and not to the scrap suppliers, because then we would know where is coming from and the exact composition"*. BT can redefine who performs the activities of, for instance, recovering materials and ensuring the elements contained in the final products.

Fifth, our findings reveal *location-specificity* (the question of where activities are performed) to be an important GVC feature that influences implementation of CE principles and the possibilities of BT to support adoption of CE in the global context. An interviewee at C4 points toward challenges with this feature: "*Our own audit teams always check [suppliers], but in case we are in a country where we don't speak the local language, we use a third party"*. Activities in terms of verification are a mix or internal and external actors. Against this setting, the capability of BT to ensure that the information recorded is accurate and secure can be considered to aid novel solutions to location issues.

Finally, our findings suggest the need for functional *governance* (how activities are organized) is an integral feature of GVCs influencing the relationship between BT and CE. The scope of the companies is conventionally limited and hence, the governance in the CE GVC needs to be reconfigured from an innovative point of view. BT seems to be critical is the long-term sustainability and CE goals that the companies have set. C4 representative notes: "*The goal is to be the world's first fossil-free steel, with no carbon footprint in the value chain"* and M2 expects "*to become climate-neutral by 2030."* To achieve such goals, companies must not only broaden their scope and integrate new technologies, but also consider new actors and ways to operate and organise activities. Such new configuration seems to necessitate an environment that is immutable, verifiable, and decentralized. Likewise, the permanency and immutability of transactions are essential for long-term goals. We suggest that the relationship of CE, GVC and BT is a constant interaction supporting one another.

While some of the GVC features identified in our empirical analysis have already been captured by existing studies (see, Kouhizadeh, et al., 2020; Nandi, et al., 2021), our study focuses on them more explicitly. We argue that by acknowledging those features that have a critical role – yet may be highly dynamic in terms of how they manifest in practice – it is possible to better organize BT so that the 3Rs will be promoted through innovative approaches. We also argue that firms wanting to achieve long-term goals need to design innovative interactions with the described GVC features to seize CE opportunities (See figure 2). The final section of this paper summarizes these aspects.

4 Discussion and conclusions

Motivated by the calls for examination of the interplay of blockchain technology and circular economy as a factor that could promote sustainable development and innovation (Böckel et al., 2021; Upadhyay et al., 2021) in a global scale, we set out to study how features of a firm's global value chain connect to the perceived opportunities and challenges brought by the interaction of blockchain and circular economy and the related innovation.

Our study indicates that there are important opportunities and challenges related to BT and CE implementation, and that many of these relate to them both emerging in global context (Alves Ferreira Cruz, Lopes, Faria, and Rosado da Cruz, 2021). The notably complex global context may limit visibility needed for CE, and under varied regulation, cultures, and other such factors, BT may not be always (fully) available (Yano et al, 2020).

Understanding the construction of the global value chains may, however, allow identifying those specific aspects of BT-CE interaction which hold the most promise. In our study, the empirical evidence suggests that BT connects to CE in the GVCs in terms of transparency, security, dispersion, control, location, and governance. The innovative approaches brought by BT can provide the means to address these features of global value chains in a way that supports innovation on reducing waste, reusing materials, and recycling. Explicit acknowledgement of transparency, security, dispersion, control, location, and governance also addresses the acceptance and management tensions present in BT-CE interaction and related innovation (van der Byl and Slawinski, 2015); in GVC context, it is possible to support demonstration of sustainability through open approaches within the value chains, yet simultaneously secure value chain members' individual competitive advantages. By considering BT and CE as belonging to a system, the issue of tension can be addressed more effectively.

Our study contributes to existing theorizing by explicitly connecting BT, CE and GVCs. We argue that the system thinking (see, e.g., Meadows, 2008) as a common ground to these all allows tapping into the interplay and tensions present in BT-CE linkage as new innovative approaches are adopted. Although the CE speech emphasizes the need of taking a systems approach (see Capra, 1982), so far relatively little explicit discussion has emerged (Robinson, 2022). BT discussion, on the other hand, often starts from the technical aspects, rather than international strategy or sustainability (Swan, 2015, Yaga, Mell, Roby, and Scarfone, 2019). Moving towards more holistic systems thinking enables analytical approach to the opportunities and challenges related to the expansion of BT to CE context (with the 3Rs) and acknowledging the relevance of global value chains. Importantly, it adds to, and bridges CE and BT discussions.

Our study also has managerial and policy implications. MNEs face issues related variance on regulations and strictness conditional to the regions, making CE actions easily opaque. By focusing on the six features introduced in this paper, firms and policy makers may be able to find those aspects where BT has most impact, and where it may find the first applications.

Considering the findings, but also limitations of our study, such as focus on a single industry, we also propose that future research should focus on higher levels of analysis, as well as taking into account the integration of other technologies which may include features such as automation, prediction, or optimization that BT may lack. This study hopefully provides insight to get started in such work.

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