EXPLORING THE ENABLERS AND BARRIERS OF CIRCULAR ECONOMY AND BLOCKCHAIN ADOPTION IN THE CONSTRUCTION INDUSTRY

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ABSTRACT

EXPLORING THE ENABLERS AND BARRIERS OF CIRCULAR ECONOMY AND BLOCKCHAIN ADOPTION IN THE CONSTRUCTION INDUSTRY

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Due to the take, make, and dispose of principle, which is the result of the linear economy model, massive natural resource exploitation of the construction industry (CI) results in various undesired environmental side effects. The circular economy (CE) concept emerged to alleviate negative impacts and change linear processes with circular ones. In this context, the successful use of CE in the construction industry can significantly contribute to remarkable reductions in gas emissions, massive natural resource consumption, and waste generation. Moreover, integrating digital technologies, particularly blockchain (BC), into the process is claimed to accelerate and enable CE adoption and success, while several barriers hinder such adoption. In this study, the enablers and barriers of adopting CE and BC were identified using a literature review and categorized according to the Technology-Organization-Environment (TOE) framework. Next, a survey was performed to explore the perspectives of construction-related professionals regarding the effect of each enabler and barrier on CE and BC adoption. Lack of sector awareness, BC and CE experienced stakeholders, lack of sufficient incentivization, inherent properties of CI, and difficulties in changing settled habits are revealed to be the prominent factors hindering adoption. The prominent enablers are educating sector participants, increased government incentives, and new regulations. The findings of this study can support decision-makers in planning and transforming the construction industry into a blockchain-supported circular economy.

Keywords: Construction Industry, Transition, Circular Economy, Blockchain Technology, Challenging and Enabling Factors

ÖZ

İNŞAAT SEKTÖRÜNÜN BLOK ZİNCİRİ VE DÖNGÜSEL EKONOMİYE GEÇİŞİNİ ENGELLEYEN VE DESTEKLEYEN FAKTÖRLERİN İNCELENMESİ

Şahin, Ufuk
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Doğrusal ekonomi modelinin bir sonucu olan al, yap ve elden çıkar ilkesi nedeniyle, inşaat sektörünün (CI) yoğun doğal kaynak kullanımı, çevre üzerinde çeşitli istenmeyen yan etkilere neden olmaktadır. Bu olumsuz etkileri hafifletmek için doğrusal süreçleri döngüsel olanlarla değiştirmek amacıyla döngüsel ekonomi (CE) kavramı yaratılmıştır. Bu bağlamda, inşaat sektöründe döngüsel ekonominin başarılı bir şekilde kullanılması, gaz emisyonlarında, yoğun doğal kaynak kullanımında ve atık oluşumunda dikkate değer azalmalara önemli ölçüde katkıda bulunabilir. Ayrıca, dijital teknolojilerin, özellikle blok zincirinin (BC) sürece entegre edilmesinin, CE'nin benimsenmesini ve başarısını hızlandırdığı ve mümkün kıldığı iddia edilirken, çeşitli engeller bu tür bir benimsemeyi engellemektedir. Bu çalışmada, CE ve BC'nin benimsenmesine olanak sağlayan unsurlar ve engeller, bir literatür taraması kullanılarak tanımlanmış ve Teknoloji-Organizasyon-Çevre (TOE) çerçevesinde kategorize edilmiştir. Daha sonra, inşaatla ilgili profesyonellerin her bir kolaylaştırıcı ve engelin CE ve BC'nin benimsenmesi üzerindeki etkisine ilişkin bakış açılarını keşfetmek için bir anket yapılmıştır. Sektör farkındalığının ve deneyiminin az olması, yeterli teşviğin sağlanmaması, inşaat endüstrisinin kendine has benimsemeyi zorlaştırıcı özellikleri ve yerleşmiş alışkanlıkların değiştirilmesindeki zorluklar benimsenmeyi engelleyen başlıca faktörler olarak ortaya çıkmıştır. Öne çıkan kolaylaştırıcılar ise sektör paydaşlarının eğitimi, daha fazla devlet teşviğinin sağlanması ve yeni kanuni düzenlemeler yapılmasıdır. Bu çalışmanın bulguları, inşaat endüstrisini blok zinciri destekli bir döngüsel ekonomiye dönüştürme ve planlama konusunda karar vericilere destek olabilir.

Anahtar Kelimeler: İnşaat Endüstrisi, Geçiş, Döngüsel Ekonomi, Blok Zincir Teknolojisi, Engelleyen ve Kolaylaştıran Faktörler

To my family, especially Enes and Arda

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Especially in these lines, I would like to thank my family for their support at every stage of my life and would like to commemorate my dear uncle.

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ABBREVIATIONS	
AI	Artificial Intelligence
BC	Blockchain
BE	Environmental Barriers
BIM	Building Information Modelling
BO	Organizational Barriers
BT	Technological Barriers
CE	Circular Economy
CI	Construction Industry
DL	Distributed Ledger
DPoS	Delegated Proof of Stake
EU	European Union
GDP	Gross Domestic Product
ID	Identification
IoT	Internet of Things
PBFT	Practical Byzantine Fault Tolerance
PoA	Proof of Activity
PoB	Proof of Burn
PoC	Proof of Capacity
PoET	Proof of Elapsed Time

PoI	Proof of Importance
PoO	Proof of Ownership
PoP	Proof of Publication
PoR	Proof of Retrievability
PoS	Proof of Stake
PoW	Proof of Work
IT	Information Technology
RFID	Radio Frequency Identification
TOE	Technology- Organization-Environment

CHAPTER 1

INTRODUCTION

This chapter includes an overview of the construction industry’s current position and the problem statement. In addition, this chapter explains the aim and scope, and organization of the thesis.

1.1 Current Position of the Construction Industry

The construction industry (CI) provides the needed foundation for society's social and economic development (Mojumder & Singh, 2021). The CI's employment rate in the world’s workable population is 7 %. Similarly, 13 % of the global gross domestic product (GDP) is spent on construction-related works (Barbosa et al., 2017).

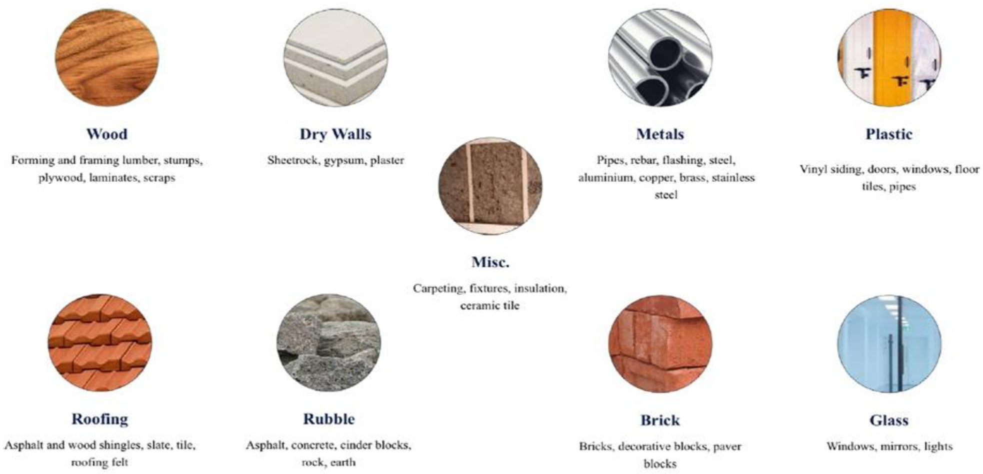

Figure 1.1. Resources used in the CI cause waste generation (Jain, 2021)

On the other hand, the sector requires intensive use of resources such as concrete, aluminum, steel, fresh water, and wood during the construction and post-construction stages. As a result of high-level resource consumption, the significant ratio of generated waste and emitted greenhouse gas on a global scale belongs to CI-related activities (Elghaish et al., 2022). As shown in Figure 1.2, the 2021 circularity gap report states that housing has the second largest footprint globally with 13.5 billion tonnes of emissions (Circle Economy, 2021). In addition, the sector has low productivity rates, intense non-value-added activities, and physically demanding methods (Ghosh et al., 2020).

Figure 1.2. The global resource and emissions footprint behind (Circle Economy, 2021)

All these negative factors decrease the sector's profitability and increase the burden on the environment. To crown it all, the need for the CI has been growing due to the increasing population and aging infrastructure and superstructure. Hence, the previously mentioned low profitability and the environmental burden will continue to increase unless a change in the working method is implemented.

Connectedly, the mainstream model affecting the way of working in the CI is a linear economy model. It depends on continuously extracting raw materials, processing them to produce final products, then using, and finally disposing of building materials. This model contains several risks (e.g., supply breaks and higher resource prices) for the CI stakeholders, such as clients, contractors, and supply chain members (Elghais et al., 2022). This model also includes environmental risks because not the needed attention has been paid to environmental topics that emerged due to CI-related actions (Vrijhoef & Koskela, 1999).

1.2 The Need for the Circular Economy (CE)

A paradigm shift from a linear to a circular economy has emerged to resolve these problems. The CE requires using resources in multiple cycles to gain value and decrease waste and consumption of fresh resource materials (Lewandowski, 2016). In general, acceptance of the CE concept in the CI will benefit both stakeholders and the environment. In Figure 1.3, the interventions vortex represents the expected reductions in greenhouse gas emissions and mass material used when written interventions, including; resource-efficient housing and reduced floor space, are met by the industry. The needed explanations can be observed on the right-hand side of Figure 1.3. As it can be interpreted from the Figure1.3, the construction and housing-related interventions (shifting to a CE-based CI from the linear one) cause the most significant reductions in gas emissions and mass material usage and expected rise in average global temperature.

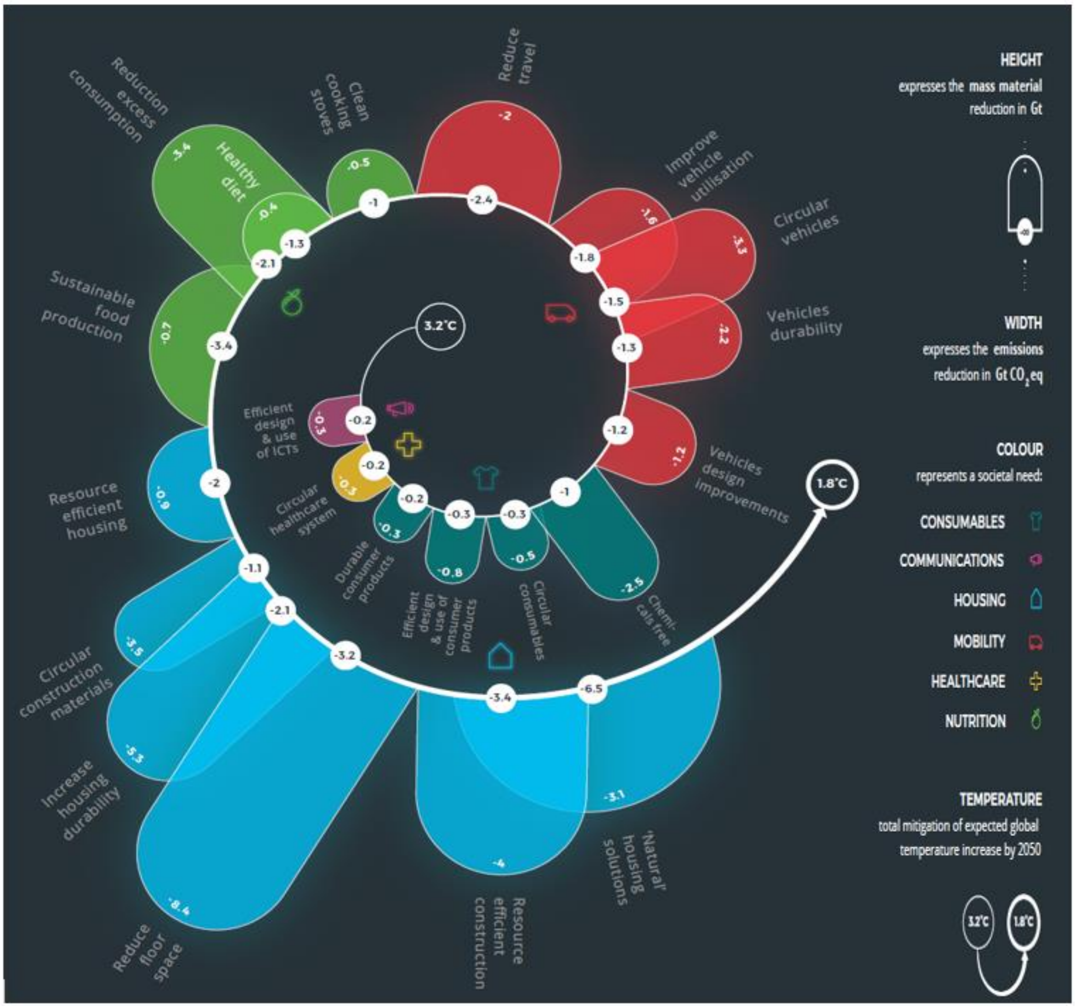

Figure 1.3. The expected results of interventions (Circle Economy, 2021)

The importance of CE adoption in the CI is mentioned in this section. In addition to the effects of CE adoption in the CI, the following section examines the impact of adding digitalization to the equation.

1.3 Blockchain (BC) in the CE and Construction Industry

Today's common concept is digitalization, which can catalyze CE adoption. Digitalization has an essential place in the successful adoption and employment of CE. Digital technologies are the fundamental enabler for the appropriate application of CE (Bressanelli et al., 2018). Boston Consulting Group selected nine technological innovations as constituents of the industry 4.0 concept (Rosa et al., 2020). These technologies are autonomous robots and vehicles, big data and analytics, additive manufacturing, simulation, horizontal/vertical system integration, augmented/virtual reality, the Internet of Things (IoT), cloud, fog, and edge technologies, and BC and cyber-security. Specifically, the IoT (Internet of Things), AI (Artificial Intelligence), and BC technologies, which can be classified under the title of industry 4.0 concept, come forward in paving the way for the transition forward circular concept (Elghaish et al., 2022).

Contrary to the previously mentioned possible advantageous use of digitalization for boosting the CE concept, CE is still an emerging topic. It has some shortfalls and challenges regarding its application tools. Connectedly, its interaction with digital technologies is still not at the desired level (Hilario da Silva & Sehnem, 2022). Specifically, despite the potential to stimulate, support, and promote the applications of the CE, BC is also an underexplored technology (Kouhizadeh et al., 2020) and has various challenges to use in the CE too. In the CI context, the BC application needs to be studied for efficient use in constructing sustainable structures (Figueiredo et al., 2022).

1.4 Aim and Scope of the Thesis

Despite the increasing interest in smart and sustainable applications, processes, industries, and cities, the BC and CE concepts are recently gaining attention in the construction industry. Individual use cases of BC and CE have been investigated in the literature. However, these concepts have not been used together widely enough and have not been entirely grasped regarding the CI. The use of BC for the CE requires a combination of sustainability and digitalization. The connection between these concepts is an immature topic in research and practice. Therefore, research is needed to analyze both topics to improve new ideas for practical innovation (Böckel et al., 2021).

To invest in practical innovations, first, the construction industry participants should be aware of such concepts. However, according to the literature, construction sector participants' awareness levels regarding CE and BC concepts and their enablers and barriers to adoption in the construction industry are not investigated in detail and are not known. Therefore, a study assessing the feedback of CI in terms of these concepts may be beneficial for industry engagement and boost adoption (Shojaei et al., 2021). Connectedly, this study aims to analyze the construction and related sector participants' perceptions with a survey study regarding BC and CE concepts and their enablers and barriers in the construction domain.

1.5 Organization of the Thesis

This study includes the following chapters;

- First chapter gives introductory information about the thesis study.
- Second chapter includes a literature review of BC and CE regarding the challenges and enablers of their individual and joint uses.
- Third chapter expresses the methodology used in the study.
- Fourth chapter includes the findings and discussion.
- Fifth chapter includes the conclusion, limitations, and future research directions.

CHAPTER 2

LITERATURE REVIEW

This chapter explains the CE and BC technology concepts and the application domains of BC technology, including the construction industry (CI). In addition, the intersection of BC and CE in the CI is discussed. Connectedly, the enablers and barriers regarding the CE, BC, and their use in the CI are presented.

2.1 Circular Economy

2.1.1 The Origin of the Circular Economy

Linear thinking, which exercises the take, make and dispose of principle, has been the mainstream and lasting idea since the inception of the third industrial revolution. It is based on producing faster to sustain economic growth while consuming fresh resources continuously and disposing of unnecessary residuals to the environment. In the linear economy model, an open-ended model, the resources are gathered from the biological cycle, such as gas, biomass, water, and other natural ones (Jorgensen & Pedersen, 2018). These raw materials are used in some value-adding steps, and final products are produced.

The next step is marketing the product to the final user. When the product changes hands, the ownership, product risks, and waste responsibility shift from the producer to the buyer (Ajwani-Ramchandani et al., 2021). Additionally, value regaining from the product, which is at the end of its useful life, is not mentioned a lot in the linear economy model (Sharma et al., 2021).

The linear economy is based on a production and consumption model (Bonciu, 2014). Contemporarily, making a profit is the main indicator of success. Making more profit is connected with more production, sales, and garbage. However, it is doubtful whether it is possible to sustain such a cycle forever (Bonciu, 2014) because of the limited resources of the Earth and the challenges of this economic model. It is significant for firms to be aware of the incredibility of the endless consumption of resources to generate value, and the linear business model necessitates a review (Casarejos et al., 2018).

As the negative effects of linear economy have been faced frequently, awareness of scientists, citizens, non-governmental organizations, and others in terms of almost coming to the limits of the linear economy increases. Based on developing awareness, the following topics, such as; increasing costs of resource extraction, waste management or environmental protection, and long-term consequences of industrial enterprises, have been criticized since the mid-1970s (Bonciu, 2014). As a result of this criticism, the need for a new economic model has been understood, and the CE concept has emerged gradually to alleviate the symptoms of the linear economic model on the adversely affected parties. Figure 2.1 depicts the comparison of circular and linear economy concepts.

Accommodating the CE instead of a linear one has gained the attention of globally known companies such as Google, Unilever, and Renault. The logic behind this is considerable expectations in terms of financial, social, and environmental benefits (Lewandowski, 2016).

Harris et al. (2021) stated that the initial usage of the CE term belongs to Pearce & Turner (1990). This emergence has been possible due to the acceptance of changing business models from linear to circular (Jorgensen & Pedersen, 2018).

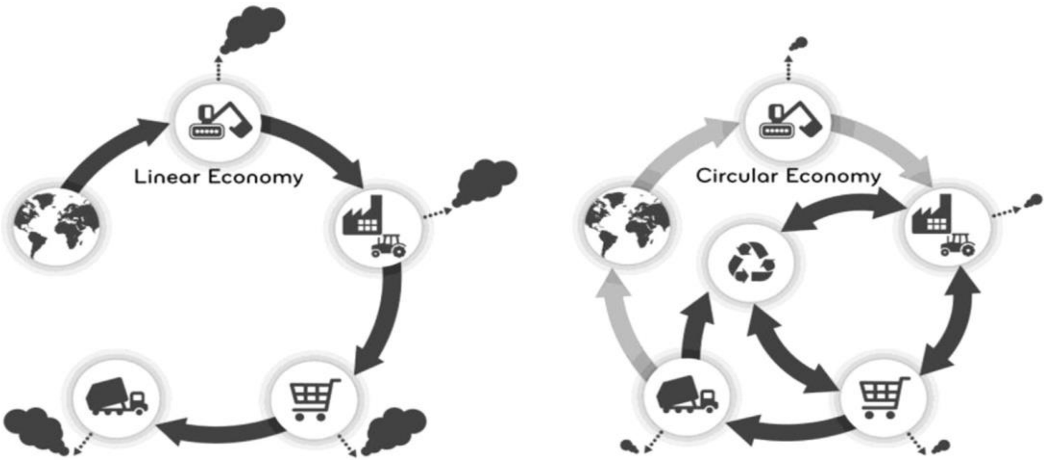

Figure 2.1. Schematic comparison of the linear economy and CE (Sauve & Sloan, 2016)

The CE is a recent approach. It is maturing gradually in research and practice (Geissdoerfer et al., 2017). The Ellen MacArthur Foundation states that a scientific and widely accepted definition of CE has not been endorsed yet (Tecchio et al., 2017). This results from the CE concept's link with many other industries. The CE is an interdisciplinary approach and includes the research topics before its invention (Geissdoerfer et al., 2017). Since each industry has its way of business, industries define CE based on their specific point of view. For example, Kirchherr et al. (2017) analyzed 114 different CE definitions in the literature. Seven definitions filtered from the literature based on historical order are presented below.

"*A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models*" (The Ellen MacArthur Foundation, 2013).

"*The circular economy refers to all activities carried out in society. It starts with the design of products, services and processes. These have to be designed in such a way as to be more durable, repairable and upgradeable, in order to allow remanufacturing and recycling for the same industry or for others*" (Bonciu, 2014).

"*The circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption. It enables key policy objectives such as generating economic growth, creating jobs, and reducing environmental impacts, including carbon emissions*" (The Ellen MacArthur Foundation, 2015b).

"*A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*" (Kirchherr et al., 2017).

"*The circular economy is a regenerative production-consumption system that aims to maintain extraction rates of resources and generation rates of wastes and emissions under suitable values for planetary boundaries, through closing the system, reducing its size and maintaining the resource's value as long as possible within the system, mainly leaning on design and education, and with capacity to be implemented at any scale*" (Suarez-Eiroa et al., 2019).

"*An economic system restorative and regenerative by design, implemented by one or more supply chain actors through one or more of the four building blocks (circular product design, serviced business models, reverse logistics and enablers) in order to replace the end-of-life concept with reducing, alternatively reusing, recycling and* *recovering materials in production, distribution and consumption processes, for both technical and biological materials, with the aim to accomplish sustainable development*" (Bressanelli et al., 2019).

"*The circular economy (CE) is a more holistic approach that advocates towards extracting the value from the waste and reaching sustainability goals*" (Sharma et al., 2021).

2.1.2 What Does Circular Economy Offer?

In CE, the initial resources may be from the environment, but then the waste of the products should become the new production step's resources endlessly (Bonciu, 2014). The adoption of CE leads companies to use resources in multiple cycles (Lewandowski, 2016). Therefore, the emergence of the CE has led to a convenient atmosphere for a significant reduction in waste generation while creating economic and financial benefits for companies and communities (Erol et al., 2022). In other words, the CE model paves the way for a decent framework for shifting business models toward sustainable development. Economic growth will be separated from environmental pressure when the desired sustainable development purpose is reached (Ghisellini et al., 2016). After that point, the environmental hesitations will be solved, and continuous development and community well-being will be possible at a higher level than today.

In addition, the position of the CE is fundamental in industrial production, resource or material improvement, and minimizing energy usage (Hilario da Silva & Sehnem, 2022). Connectedly, the CE tries to benefit society, the environment, and the economy to form balance and unity. The pictural representation of the CE's position can be seen in Figure 2.2.

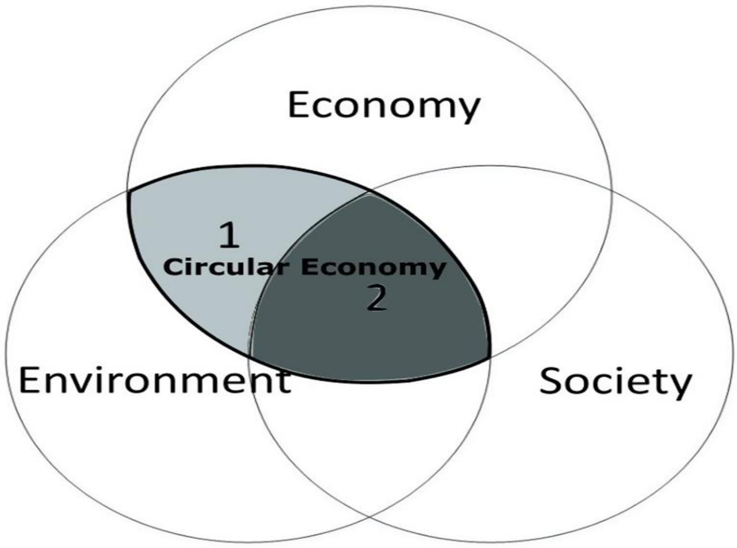

Figure 2.2. Pictural definition of CE (Suarez-Eiroa et al., 2019)

The CE helps companies to use resources in multiple cycles to generate value and diminish waste and consumption. The details can be found when the business models' input, transformation process, and output side are investigated (Lewandowski, 2016). The mentioned cycles, input, and output sides can be analyzed in Figure 2.3.

The CE strongly relates to today's industrial system since it is needed to solve the problems of today's industrial design problems. Therefore, the CE principle has the potential to be nested in every step of working for an industrial organization. Figure 2.3 is named "*Circular economy – an industrial system that is restorative and regenerative by design*" by (The Ellen MacArthur Foundation, 2015b) to stress the industrial point of view.

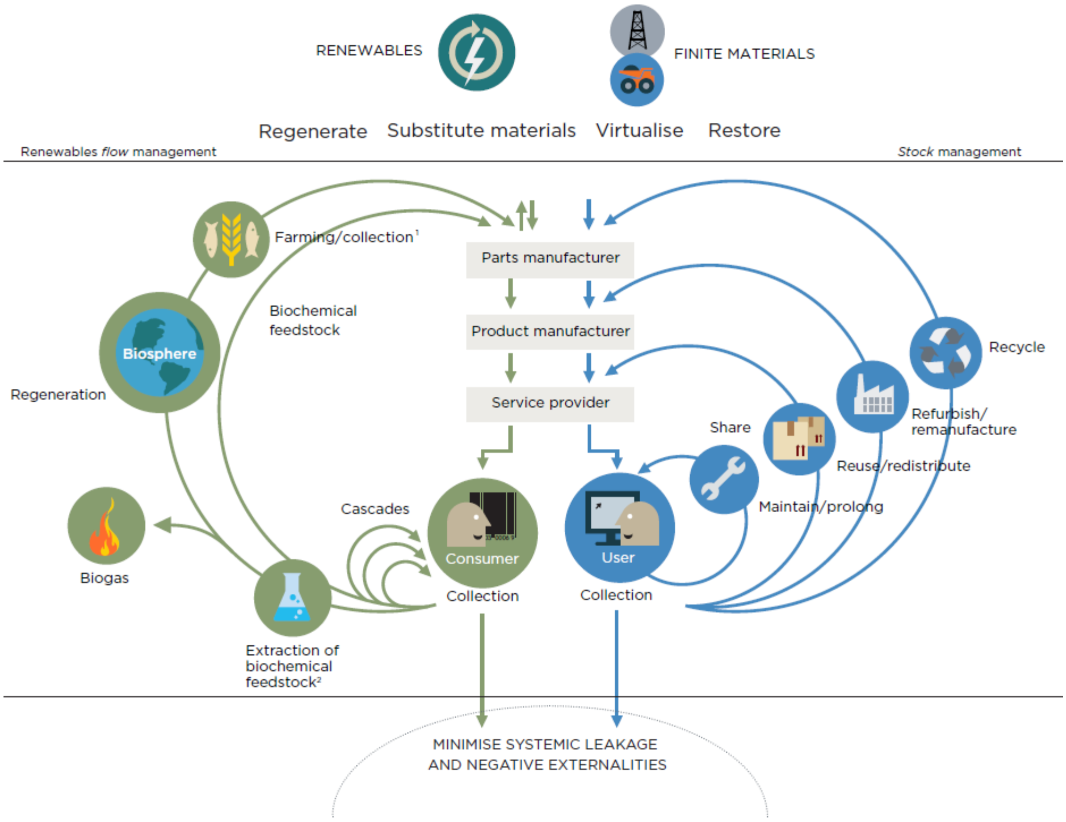

Figure 2.3. Butterfly diagram showing how sources move through the CE (The Ellen MacArthur Foundation, 2015b)

As highlighted in the aforementioned definitions of CE collected from the literature, the circular system depicted in Figure 2.3 demonstrates how to keep assets and materials at their highest possible value. The left-hand side green cycles in Figure 2.3 show the biological cycles, whereas the right-hand side blue cycles demonstrate the built environment cycles or technical cycles. An important effort is exerted to delay sending the material or any asset to the next cycle, for example, from the reuse cycle to the remanufacturing cycle. The shorter the loop, the less energy will be required to make the product reusable. Therefore, potentially more profit for the firm can be gained by trying to keep any product within inner loops in any project.

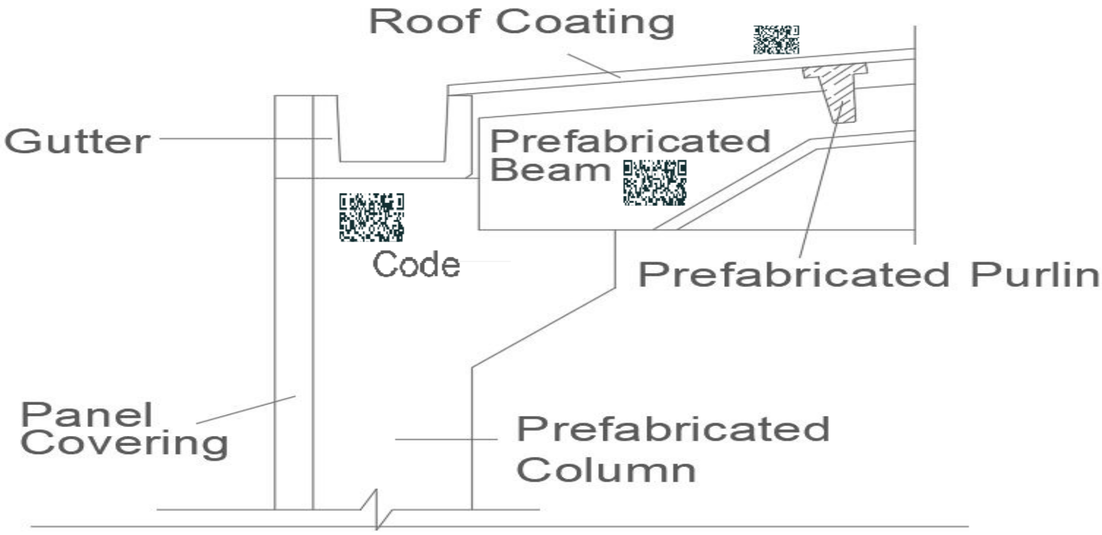

Figure 2.4. A prefabricated steel structure section

To illustrate, in Figure 2.4, a prefabricated steel structure section is demonstrated. The prefabricated members were transported from the production facility to the site and were mantled together to form the structure many years ago. The most favorable scenario is to continue to use the existing building with minor maintenance work. If the structure's service life ends and the members cannot be used in their current position, the structural members will be dismantled. Then, they will be relocated if it is possible to reuse structural members (purlin, beam, column) if they were not damaged. Therefore, they will be moved within the possible smallest loop, and there will be the second highest value for the end-user because new structural members will not be needed or bought.

Additionally, it is better for the environment because there will not be new production, waste, or energy consumption. The only burden is transportation for the end user and the environment. So far, the process is in the reuse/redistribute cycle, as seen in Figure 2.3. If reusing existing members is impossible, the outer loop is to refurbish/remanufacture. The members will be reformed to be used, and energy consumption will be increased when compared to the previous cycle's energy consumption. The profit also decreases.

This logic continues to the outermost cycle, which is recycling. It is an even better alternative regarding naming structural members as waste. The value gaining also continues in this cycle. As illustrated, using resources in multiple cycles generates value for the companies.

2.1.3 Different Circular Economy Approaches in the Literature

Bonciu (2014) proposes four different aspects to define the borders of the CE. The first one is the holistic approach. In terms of the holistic approach, the CE includes all activities performed in society, starting from designing products, services, and processes. The products, services, and processes should be planned to be more durable, repairable, and upgradable to allow recycling and remanufacturing for intra and inter-industries (Bonciu, 2014). This idea is important because, in the previous paragraph, the existing structural members are considered for the multiple-cycle process to gain value. However, the initial production plan and characteristics of the products are essential for the remaining life cycle of the product.

The next aspect is related to the scale. In detail, by accepting to use CE, the companies will select the remanufacturing, reusing, and recycling of the products for their business activities. Connectedly, as the scale of such an implementation grows, the energy and raw materials needed for production will be diminished (Bonciu, 2014). It is seen that using existing materials decreases the energy required for production and, accordingly, the cost of production.

The third aspect stresses the requirement of a specific legislative and institutional framework covering social and economic activity. The final one is about developing particular indicators to ease the applicability and monitoring of the CE, for example, controlling the increase in GDP concerning consumed raw materials (Bonciu, 2014).

In addition to Bonciu's approach, Hilario da Silva & Sehnem (2022) state that the CE principle is constructed on many pillars.

The first pillar is the Rs principle. Numerous R frameworks were used in the literature and practice (Hilario da Silva & Sehnem, 2022). As the sustainability and circularity consciousness increased and their usage area enlarged, new Rs were added to the literature. The 3R principle (Reduce, Reuse, and Recycle) is the essence of the CE Promotion Law (Kirchherr et al., 2017). The CE Promotion Law highlighted the management and promotion of 3R activities in the industrial sector (Sakai et al., 2011).

The European Union (EU) Waste Framework Directive used the 4R framework by adding “Recover” to the 3R framework (Kirchherr et al., 2017). As the need for product modularity increases for sustainable design and manufacturing, the 6R framework was introduced (Yan & Feng, 2014). The 6R framework includes recover, reuse, recycle, redesign, reduce, and remanufacture. Recover, redesign and remanufacture concepts were introduced by the 6R framework to the known 3R principle. The 6R framework is accepted as the main standard of sustainable design and manufacturing (Yan & Feng, 2014). Next, the 9R framework includes refusing, reducing, reusing, repairing, refurbishing, remanufacturing, repurposing, recycling, and recovery terms (van Buren et al., 2016). One more perspective for the Rs is the 10R framework, including refusing, rethinking, reducing, reusing, repairing, refurbishing, remanufacturing, repurposing, recycling, and recovering. The 10R perspective can make it easier for companies to get a competitive advantage (Bag et al., 2021). Figure 2.5 represents the mentioned Rs. Figure 2.6 represents a different point of view regarding the use of R strategies in CE.

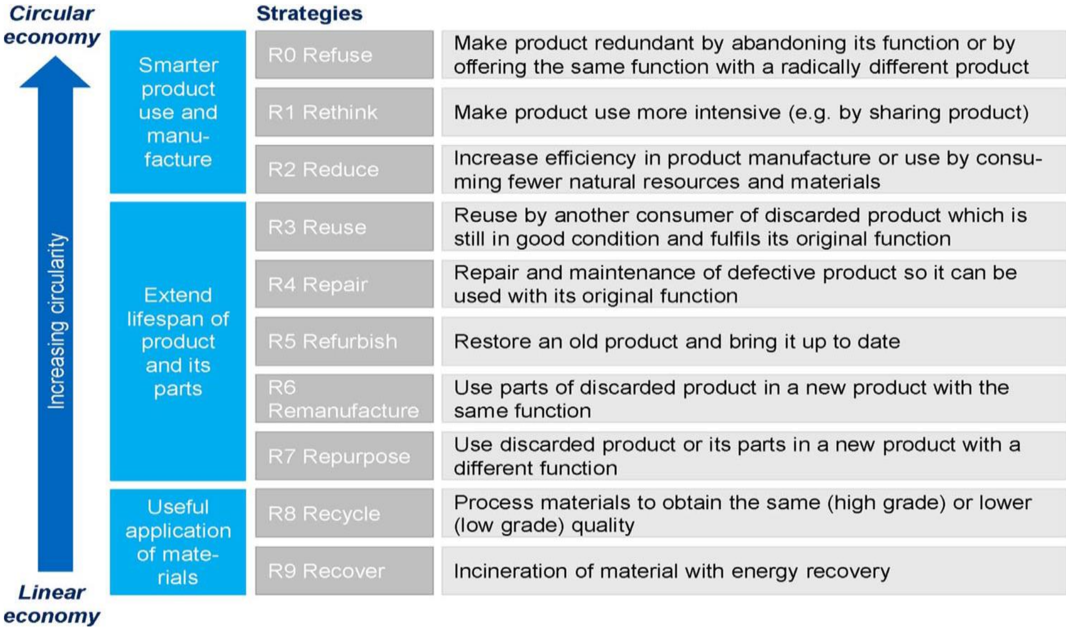

Figure 2.5. The priority of circularity strategies (Kirchherr et al., 2017)

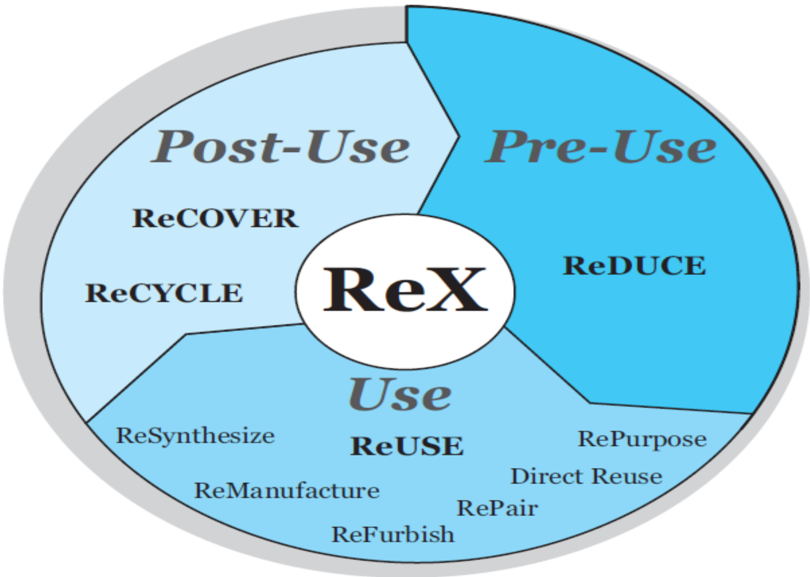

Figure 2.6. ReX strategies (Potting et al., 2017)

The second pillar of CE is the product service system (Hilario da Silva & Sehnem, 2022), which is a business model (Wang et al., 2020). Product service systems envelop products, services, and agent networks. They support infrastructure that operates unbrokenly to gain a competitive advantage, satisfy customer demands, and reduce environmental burdens (Hilario da Silva & Sehnem, 2022).

The next pillar is industrial symbiosis, which is a system of industrial ecology that forms a basis for it (Hilario da Silva & Sehnem, 2022). Industrial symbiosis aims to operate jointly beneficial cooperation within organizations by sharing by-products, residual materials, resources, water, and energy. Therefore, all the participants take advantage of it. In industrial symbiosis, energy and material consumption are optimized, residue formation is minimized, and the output of a particular process is the input of other processes (Sehnem et al., 2019).

The final pillar is the Resolve model, as depicted in Table 2.1. This model proposes six business actions to enable CE fundamentals (Lewandowski, 2016). These are regenerate, share, optimize, loop, virtualize, and exchange. The Resolve model helps countries and businesses to develop circular strategies and growth dynamism (The Ellen MacArthur Foundation, 2015b).

Table 2.1. Resolve framework explanation (Ellen MacArthur Foundation, 2015b; Lewandowski, 2016; Kouhizadeh et al., 2020)

RE-GENERATE	Indicates the progress through renewable energy and materials
	Includes returning recovered biological resources to the biosphere
	Focuses on reclaiming, retaining and rehabilitating the health of ecosystems
SHARE	Aims to maximize the utilization of products by sharing (peer-to-peer or public) them among users, instead of individual owning while minimizing the waste and duplication
	Products and materials are recollected for reuse / secondhand market
	Prolonging the usable period of materials and products in their lifecycle through maintenance, repair and design for durability and upgradability
OPTIMIZE	Aims to diminish non-value-added actions in manufacturing, operating and consuming. In other words, aims to remove waste in the supply chain and production process.
	To increase the performance and efficiency of a product thanks to technology implementation
	Integrating big data into the process for the automation, remote sensing
LOOP	Loop is directly the opposite of "linear". Instead of make-use-dispose, the materials, resources and energy can be reused in a closed-loop activity.
	The inner loops have a higher priority.
	Aims to remanufacture the components and products, recycle materials
VIRTUALIZE	Aims to deliver utility in a virtual environment instead of materially. This may replace or delay actual material consumption.
	Aims to dematerialize the processes directly or indirectly.
EXCHANGE	It is about enhancing processes with the help of new technologies and doing things in a new way instead of old ways.
	Replacing old materials with green non-renewable materials used in production processes.
	Choosing new products and services

To sum up, the CE has a remarkable capability for sustainable development due to its potential to change business models, close resource loops, and reduce waste (Geissdoerfer et al., 2017). In other words, the CE has a driving force to reach desired sustainability level more easily (Blomsma & Brennan, 2017). Technological enhancements contribute to closing the loop by supplying accurate information, slowing the material loop, and shortening the loop thanks to enhanced efficiency in resource usage (Antikainen et al., 2018). Connectedly, digital technology is a catalyst for the CE. The faster advancement of CE practices and business models is possible with digital technologies (Rosa et al., 2020), especially with the use of industry 4.0 tools. Yildizbasi (2021) states that BC technology can be accepted as one of the industry 4.0 instruments. It provides security, privacy, immutability, decentralized environment and increases the trust between participants. Therefore, BC is a superior technology that can be used with the CE.

2.2 Blockchain Technology

2.2.1 Motivation for Blockchain Technology

Centralization represents a single authority's control over any organization that must be managed. This organization can be a bank, a company, a government, and so on. It is possible to see examples of this centralized structure frequently in daily life. The basic illustration of this centralized formation can be seen in the financial environment.

Although the current financial system works today, there are also some problems with the existing financial environment due to its centralized structure. Hackers can corrupt the data from a single centralized node. Errors in the data center of the central entity cause undesired results for the related parties (Rajasekaran et al., 2022). Making money exchange on the system is subjected to a transfer fee. Long contract documents are prepared to establish trust between parties and prevent their rights in any dispute circumstance. The mentioned problems with the existing structure are not the whole list.

In connection with these drawbacks, in 2008, a person or a group, even today the exact identity is not known, "Satoshi Nakamoto," published a study titled "Bitcoin: A Peer-to-Peer Electronic Cash System" (Huang et al., 2022). Bitcoin was presented as a digital currency that can work without any central system and where the needed measures are taken against the manipulation interference of its users or outsiders.

The presented system by "Satoshi Nakamoto," records the data based on a previously determined consensus mechanism through strong cryptography techniques. Although the BC term does not exist in Nakamoto's study, the methods and schemes used in the article paved the way for the formation of the BC concept (Usta & Doğantekin, 2018).

BC has a strong relationship with the terms “data,” “database,” “network technologies,” and “cryptography.” These terms form the required infrastructure for the existence of BC technology. To illustrate, the “cryptographically” stored “data” is kept by distributing a copy of them to all users in the “network” instead of packaging all data in a central system. In short, the logic behind BC technology is to form a secure data recording mechanism (e.g., bitcoin transaction data) without any need for centralized structures (Usta & Doğantekin, 2018).

Figure 2.7. Centralized- trusted third-party environment (Aggarwal & Kumar, 2021)

Connectedly, the decentralization concept comes to the stage. In a decentralized environment, every transaction in the system is executed by two nodes at a time, and there is no need for third-party validation. Therefore, it allows BC to work independently from any central authority (Zarrin et al., 2021). In short, decentralization comprises the delivery of authority and power from a single node to all participants in a network.

2.2.2 Key Characteristics of Blockchain Technology

There are different points of view regarding the features of BC. Zheng et al. (2018) stated that BC has the following main features; persistency, anonymity, auditability, and decentralization. Additionally, Figure 2.8 prepared by Aggarwal & Kumar (2021) also demonstrates the features of blockchain. Multiple factors play a role in characterizing the BC system, starting from its type (e.g., private or public) to its decentralization (Viriyasitavat & Hoonsopon, 2019). From their point of view, the list of the features of BC is as follows: permitted or permissionless, decentralization, persistency, validity, anonymity and identity, auditability, closedness, and openness. Moreover, Monrat et al. (2019) also accepted decentralization, persistency, anonymity, and auditability as characteristics of BC. Mentioned characteristics of BC technology will be explained within the following pages.

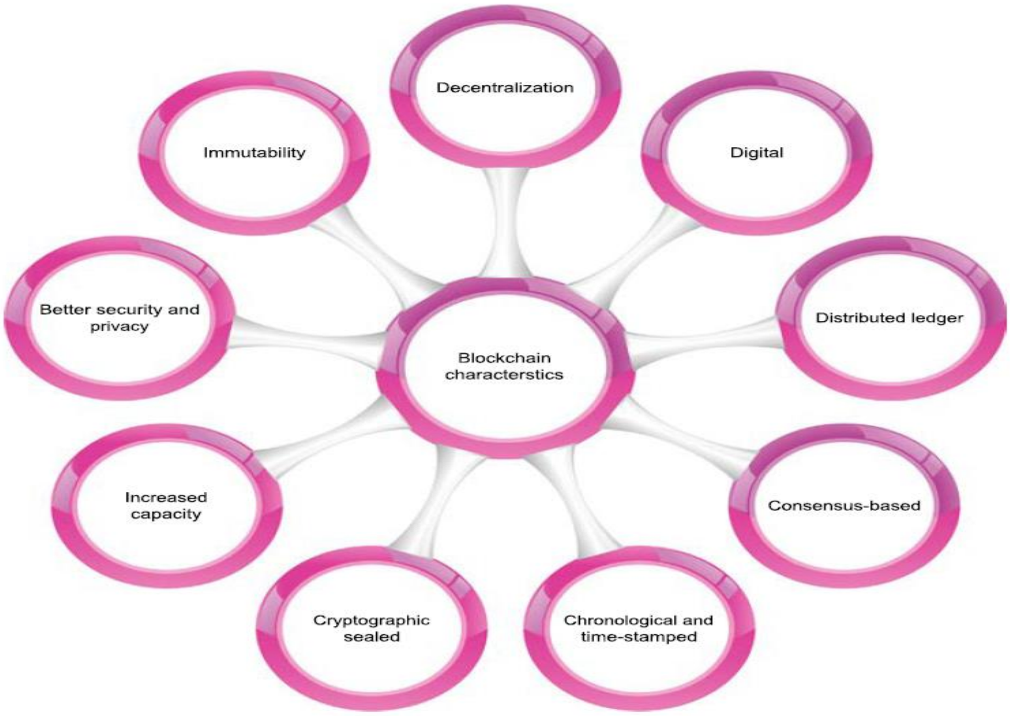

Figure 2.8. Features of the BC (Aggarwal & Kumar, 2021)

2.2.2.1 Persistency

It is about reliable miners' validation requirements of any completed peer-to-peer transaction. Since the information about the transaction is shared with all parties, confirmed by them, and recorded in blocks, it is tough to tamper. Therefore, persistence has a strong relation with immutability. The stored data in multiple nodes cannot be deleted or altered. In such a case, falsification is very easy to be reached (Zarrin et al., 2021; Zheng et al., 2018).

2.2.2.2 Auditability

Auditability is basically about the traceability and verifiability of each operation or transaction in the BC environment (Zarrin et al., 2021). As mentioned previously, each operation in the BC environment is recorded and confirmed with a timestamp. Therefore, it is simple for users to verify and trace the footprint of previous operations using any distributed network node as a point of access. It enhances the data traceability and transparency in the BC (Zheng et al., 2018). BC can boost auditability and transparency for financial transactions (Asante et al., 2021).

2.2.2.3 Anonymity

Anonymity is about using generated unique IDs in the BC environment. The main objective of this concept is to ensure the anonymity of miners in the network (Zarrin et al., 2021). Additionally, one of the primary purposes of BC is to protect the anonymity of each transaction. In other words, hackers cannot reach the user's personal information through data investigation (An et al., 2022). There is no need for a central body to store users' personal information. Therefore, the privacy and anonymity of transactions in the BC environment are secured. It is also mentioned in the literature that BC cannot guarantee perfect privacy protection (Zheng et al., 2018).

2.2.2.4 Decentralization

In the usual centralized system, verification by a trusted third party is a need, such as in transactions through banks. Cost and performance bottlenecks and data security problems are the main challenges for the centralized system. On the other hand, in a decentralized structure, there is no need for a mediator. Additionally, consensus mechanisms provide the security of information in the distributed network (Zheng et al., 2017).

2.2.3 Structural Overview of Blockchain

Figure 2.9 illustrates the implementation steps of BC and, at the same time, shows the general view of BC-related terms.

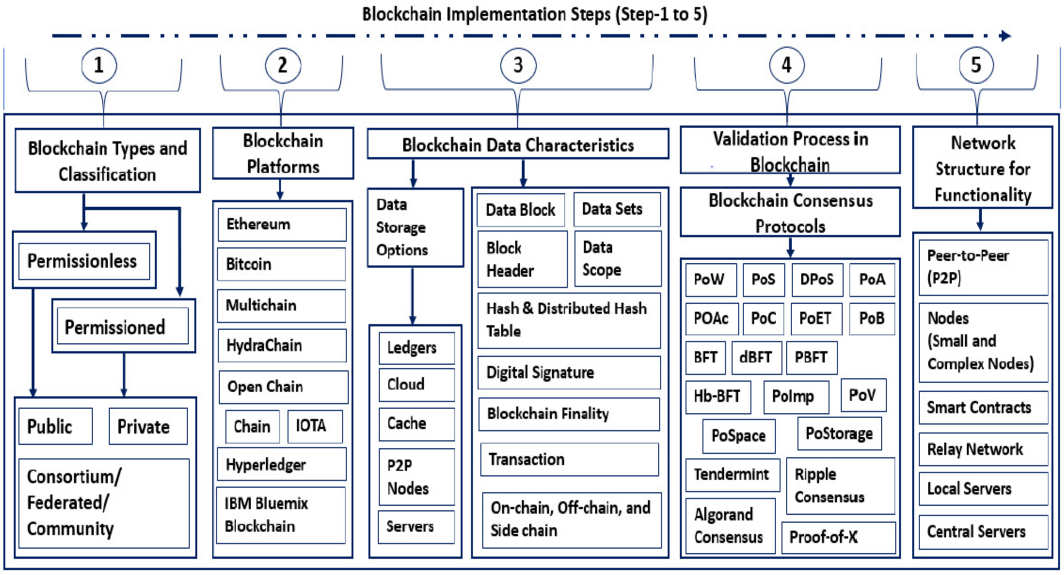

Figure 2.9. BC implementation steps (Kumar & Chopra, 2022)

2.2.3.1 Node

Each device (machine) and user in the distributed BC network is called a node. Nodes should make a consensus for every block added to the block queue (Usta & Doğantekin, 2018). A complete copy of blocks and historical transactions is stored at mining nodes, and these nodes produce new blocks as a result of the transaction verification process (Chen et al., 2021).

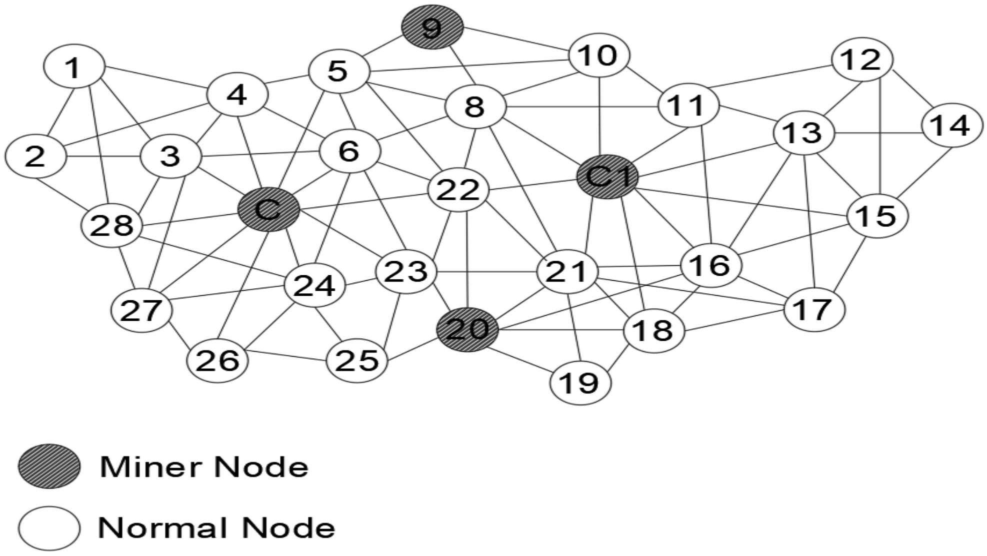

Figure 2.10. Nodes in the distributed BC network (adapted from Aggarwal & Kumar, 2021)

2.2.3.2 Miners

Nodes that are capable of adding new blocks to the BC system are named "miners" (Dos Santos et al., 2019). The miners are the stakeholders of BC networks who clarify the cryptographic obstacles and validate transactions. As a result, they earn cryptocurrency for the fulfillment of mentioned work (Dindarian & Chakravarthy, 2020). In addition, a BC network gives a chance to any network member to behave both as a server (to approve and conclude transactions) and a client (to issue transactions) (Xiao et al., 2020).

2.2.3.3 Hash

Barely hashing is a method used to retrieve or store data records from the database. Secure storage of any information or data can be achieved using hash techniques (Aggarwal & Kumar, 2021). Cryptographic techniques are the basis for BC technology. Connectedly, the cryptographic hash function forms the fundamental part of the technology (Seok et al., 2019). Hashing is not an encryption technique; it is a one-way condensing cryptographic function; hence, it is impossible to decrypt it back to the original file or text. Since the cryptographic hash is a kind of digital signature for a text or a data file (Aggarwal & Kumar, 2021), the hash function's performance is essential for BC's success (Seok et al., 2019) in terms of security.

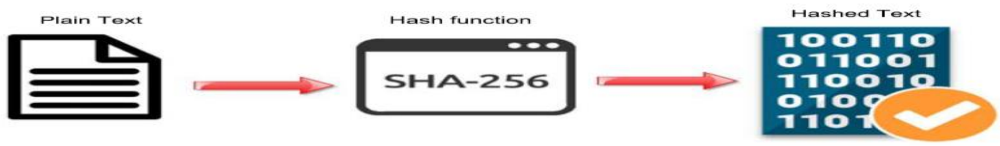

Figure 2.11. Hash function turns plain text or files to condensed hashed text (Aggarwal & Kumar, 2021)

2.2.3.4 Digital Signatures

Authentication, integrity, and nonrepudiation criteria for electronic documents are ensured by digital signatures, which are cryptographic mechanisms needed to sign and verify message signatures. Message integrity means that there was no alteration in the message after the sender sent it. Message repudiation implies that both the sender and the receiver cannot refuse the document after signing and verification of the document. Message authentication indicates that there is no alteration in the message during transmission and that message was created, signed, and sent by a known sender (Aggarwal & Kumar, 2021).

2.2.3.5 Merkle Root Hash

The calculation of the Merkle root hash is depicted in Figure 2.12. The initial texts (Tx0 … Tx3) are converted into hashes with the help of hash functions. Next, each text's hashes are matched, and they are passed through another hashing algorithm. This process is continued until reaching a final Merkle root hash (Rajasekaran et al., 2022). As a result of these continuous hashing processes, it is possible to store multiple records in one block. Relatedly, the root hash represents the entire previous data and can be seen as a fingerprint of all previous data (Aggarwal & Kumar, 2021). Simplifying the data into hashes and, finally, to one root hash will increase the productivity of the general BC environment.

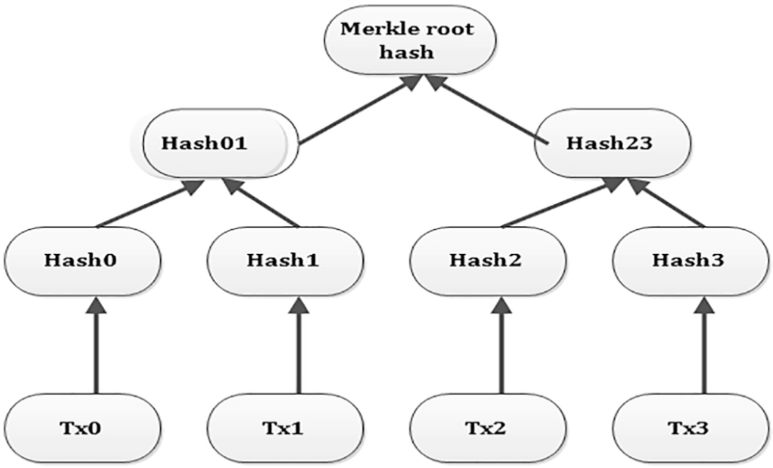

Figure 2.12. Calculation steps of Merkle root hash (Rajasekaran et al., 2022)

2.2.3.6 Nonce Value

It is simply a random number related to some data. This number is added to each block. It is used only one time. The miners find the nonce value by solving the cryptographic puzzle (Raj, 2021).

2.2.3.7 Mining

The addition of a new block to the BC network following the validation process of a block is called mining (Kumar & Chopra, 2022). Mining is an operation of joining a block to the BC. Having the privilege to add a block to the BC requires one to be the first node that finds the nonce value satisfying the proof of work. Various strategies, namely consensus protocols/validation processes (Kumar & Chopra, 2022), are listed to determine which miner will have the right to add the developed block to the BC (Rajasekaran et al., 2022). The list of consensus protocols can be seen in the 4th column in Figure 2.9.

2.2.3.8 Consensus Protocol

The consensus mechanism has fault-tolerant properties, and the leading purpose of using BC is to reach an agreement on a single point among distributed nodes (Aggarwal & Kumar, 2021). A consensus algorithm mechanism is an essential factor for DL technology. Synchronization of DL between different nodes is possible through a consensus algorithm (Chowdhury et al., 2019). The protocol is a set of rules in which every node (peer) in the network must act within the borders of consensus (Xiao et al., 2020).

The algorithm draws the way for the nodes to settle agreements and update the BC network (Zarrin et al., 2021). Before adding any transaction to the immutable data storage, the whole network makes a consensus (Xu et al., 2016). Therefore, consensus protocol constitutes the trust between BC users, according to (Wang et al., 2019), between trustless nodes, in terms of transferring and updating data among end-users (Rajasekaran et al., 2022).

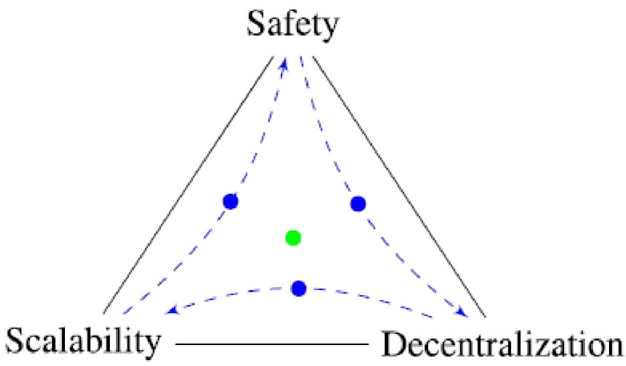

Figure 2.13. Dealing with the BC trilemma (Leonardos et al., 2020)

Any consensus protocol aims to balance scalability, decentralization, and safety variables better. This situation is displayed in Figure 2.13. The green point is the desired consensus protocol. The blue ones are the protocols that are turning around the ideal situation (Leonardos et al., 2020).

In addition, since the first node solving the puzzle gains the right to add the block to the chain and earn some cryptocurrency as a reward, fairness is an important topic in BC consensus protocols (Aggarwal & Kumar, 2021). It is not only about the monetary topics, and fairness is a significant issue regarding the voting process in BC networks. Figure 2.14 illustrates the fairness mechanism.

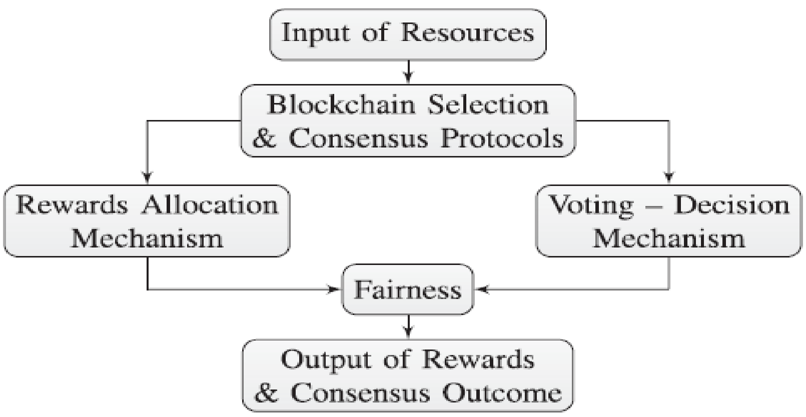

Figure 2.14. Reward and voting mechanism in consensus protocols (Leonardos et al., 2020)

There are various consensus protocols, and some of them are as follows; proof of work (PoW), proof of stake (PoS), delegated proof of stake (DPoS), practical Byzantine fault tolerance (PBFT), proof of capacity (PoC), proof of activity (PoA), proof of publication (PoP), proof of elapsed time (PoET), proof of importance (PoI), proof of retrievability (PoR), proof of burn (PoB), and finally proof of ownership (PoO) (Aggarwal & Kumar, 2021). Among all these protocols, the PoW, PoS, and DPoS will be explained in detail.

2.2.3.9 Proof of Work (PoW)

It is accepted as the most frequent consensus mechanism, which is also used by bitcoin (Aggarwal & Kumar, 2021). In each round of consensus, the PoW algorithm chooses one node to develop a new block through a competition of processing power. The participating nodes in the challenge must figure out a cryptographic puzzle (Zhang & Lee, 2020). The puzzle is a hash value convincing the previously determined conditions. The miners try to find the hash satisfying the difficulty target value by keeping on changing the nonce variable (Rajasekaran et al., 2022). The node figuring out the puzzle earlier gains the right to build the new block. After the nonce value is found and requires much computational power (Zhang & Lee, 2020), the miner shares it with the other nodes, and the validation and verification processes start. Finally, the block is integrated into the chain (Rajasekaran et al., 2022). Figure 2.15 illustrates the working principle of the PoW consensus mechanism.

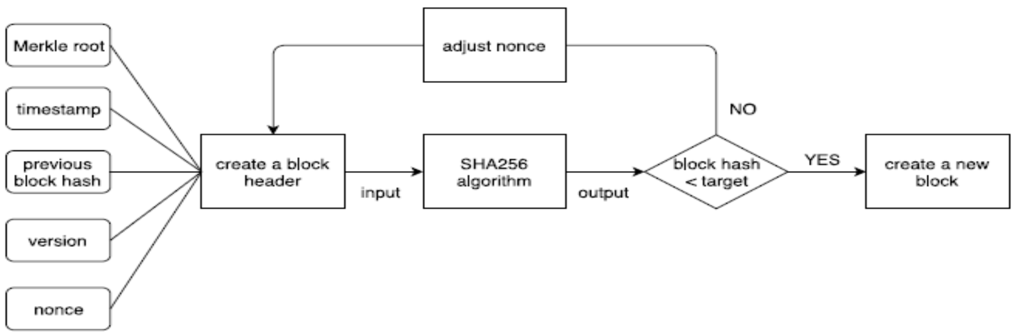

Figure 2.15. The working mechanism of PoW (Zhang & Lee, 2020)

2.2.3.10 Proof of Stake (PoS)

The second most common consensus mechanism is proof of stake. PoS is trying to deal with the energy consumption problem of PoW (Saleh, 2021). Compared to PoW, PoS consumes less energy, needs less processing time, therefore needs low computational power, and connectedly diminishes the cost (Aggarwal & Kumar, 2021). Instead of competition of miners in PoW, which is computationally complicated (Rajasekaran et al., 2022), PoS selects the stakeholder to create a new block (Saleh, 2021) in a randomized way (Aggarwal & Kumar, 2021). Having the right to create a new block depends on the amount of stake held instead of the computational power (Zhang & Lee, 2020). There are validators in the PoS mechanism rather than miners. The participants stake their money for a pre-determined period to become a validator and create a block. Having a higher stake means a greater chance of being selected as a validator and developing a new block (Aggarwal & Kumar, 2021). The puzzle in PoS is the number of coins and stakes (Zhang & Lee, 2020). The selection probability also depends on the length of time interval in which coins are staked (Aggarwal & Kumar, 2021). Figure 2.16 illustrates the working principle of the PoS consensus mechanism.

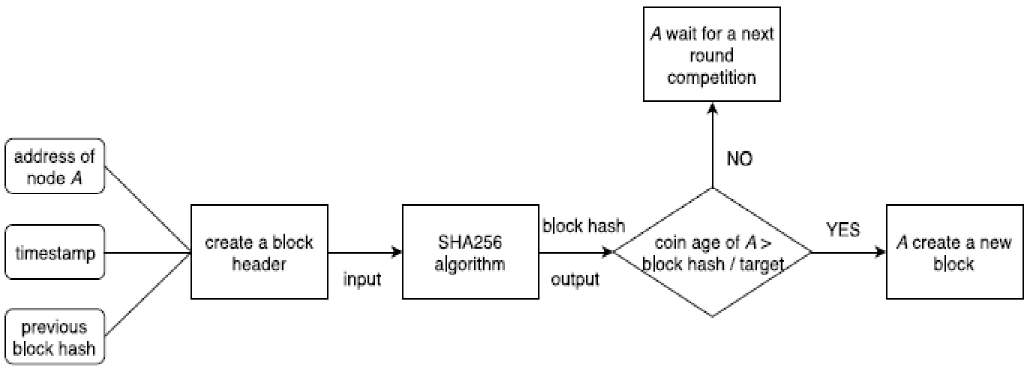

Figure 2.16. The working mechanism of PoS (Zhang & Lee, 2020)

2.2.3.11 Delegated Proof of Stake (DPoS)

Instead of creating blocks themselves, in delegated proof of stake, the nodes vote to select delegates who will produce blocks (Zhang & Lee, 2020). The weight of votes depends on the coins staked by the voters; the more coin staked, the more weight of the vote (Aggarwal & Kumar, 2021). In that way, the voters don't consume computational power. DPoS is like a parliamentary organization. The consensus is reached based on the stakeholders' votes. If the selected delegates fail to produce a block, a new election will be planned (Zhang & Lee, 2020).

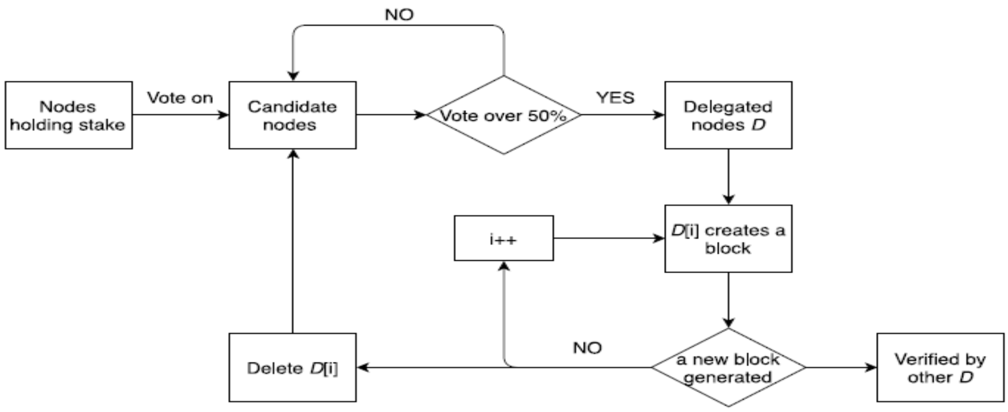

Figure 2.17. The working mechanism of DPoS (Zhang & Lee, 2020)

2.2.3.12 Distributed Ledger

It is a new way of doing business, managing personal data, and tracking products. BC is the one form of DL technology. A DL is a kind of database located across different locations (Chowdhury et al., 2019) and is shared and synchronized with a network based on a consensus. To illustrate, it keeps a record of the whole ownership history of an asset. It makes the transactions publicly known, ensuring the network is against malicious attacks. In other words, a DL is a security measure for BC technology (Raj, 2021).

2.2.3.13 Smart Contracts

BC has crucial code pieces, which are known as smart contracts. The mentioned codes permit a new sovereign environment that enhances encrypted logic. Connectedly, there is no need for a trustable third party in case of using a smart contract (Erol, Ar, Peker, & Searcy, 2022). Smart contracts are a kind of deal that is prepared (encoded) in a computer environment and can be stored on the BC. When previously agreed criteria are met, they are executed automatically. It has some advantages, such as reduced contract execution costs, increased speed, and improved quality of work (Raj, 2021).

```
pragma solidity 0.8.7;

contract VendingMachine {

    // Declare state variables of the contract
    address public owner;
    mapping (address => uint) public cupcakeBalances;

    // When 'VendingMachine' contract is deployed:
    // 1. set the deploying address as the owner of the contract
    // 2. set the deployed smart contract's cupcake balance to 100
    constructor() {
        owner = msg.sender;
        cupcakeBalances[address(this)] = 100;
    }

    // Allow the owner to increase the smart contract's cupcake balance
    function refill(uint amount) public {
        require(msg.sender == owner, "Only the owner can refill.");
        cupcakeBalances[address(this)] += amount;
    }

    // Allow anyone to purchase cupcakes
    function purchase(uint amount) public payable {
        require(msg.value >= amount * 1 ether, "You must pay at least 1 ETH per cupcake");
        require(cupcakeBalances[address(this)] >= amount, "Not enough cupcakes in stock to complete this purchase");
        cupcakeBalances[address(this)] -= amount;
        cupcakeBalances[msg.sender] += amount;
    }
}
```

Figure 2.18. A smart contract determining the working principle of a vending machine (Ethereum.org, n.d.)

2.2.3.14 Block and Blockchain

Each block is connected to the next one with encryption tech to resist the alteration of data. Blocks include a cryptographic hash value of the former block, a fresh timestamp, and transaction data or other needed data. The chain of blocks is formed when multiple blocks are connected. BC is a kind of database or a growing linear list of data records named blocks. It is a DL that builds consensus on the history of transactions (Mahmoud et al., 2019). Initiating a new transaction or any record means adding a new block to the system. Before adding a block to the queue, the majority of the miners' verification prerequisites must be satisfied (Rajasekaran et al., 2022). The verification prerequisites depend on the type of BC.

Figure 2.19 and Figure 2.20 are presented here to demonstrate the general view of block and BC concepts.

Number	Hash	Miner	Mined	Tx Count	Nonce	Fill	Size	Total Sent	Total Fees
759968	0000-bb1d	Unknown	15m 33s	2,679	1,728,635,258	133.50%	1,399,797 Bytes	30,066 BTC	0.13BTC
759967	0000-67e0	Unknown	42m 18s	2,230	3,709,844,287	138.07%	1,447,756 Bytes	6,881 BTC	0.04BTC
759966	0000-3918	Unknown	44m 41s	2,359	470,549,622	160.68%	1,684,827 Bytes	3,381 BTC	0.06BTC
759965	0000-265e	Unknown	45m 42s	3,392	1,523,288,075	139.75%	1,465,360 Bytes	30,570 BTC	0.19BTC
759964	0000-0f2f	Unknown	1h 45m 11s	3,148	406,048,676	144.44%	1,514,592 Bytes	29,410 BTC	0.09BTC
759963	0000-e0ed	Unknown	2h 10m 43s	299	3,178,951,792	11.58%	121,397 Bytes	264 BTC	0.01BTC

Figure 2.19. List of blocks and their details (Blockchain.com, n.d.)

Bitcoin Block #759,967

Mined on 10/23/2022, 15:00:50 View all Blocks

This block was mined on 10/23/2022, 15:00:50 by Binance Pool. A total of 6,881.10 BTC ($131,798,823) were sent in the block with the average transaction being 3.0857 BTC ($59,102.73). Binance Pool earned a total reward of 6.25 BTC $119,710. The reward consisted of a base reward of 6.25 BTC $119,710 with an additional 0.0382 BTC ($731.67) reward paid as fees of the 2,230 transactions which were included in the block.

Details

Hash	00000-367e0	The root node of a merkle tree, a descendant of all the hashed pairs in the tree	1,447,756
Depth	11		0×252a6000
Capacity	138.07%	Merkle Root	a5-cb
Distance	1h 42m 36s	Difficulty	35,610,794,164,371.65
BTC	6,881.0976	Nonce	3,709,844,287
Value	$131,798,823	Bits	386,393,970
Value Today	$131,838,183	Weight	3,993,499 WU
Average Value	3.0856940090 BTC	Median Time	Oct 23, 2022, 2:32:54 PM
Median Value	0.01363572 BTC	Minted	6.25 BTC
Input Value	6,881.14 BTC	Reward	6.28822393 BTC
Output Value	6,887.39 BTC	Mined on	Oct 23, 2022, 3:00:50 PM
Transactions	2,230	Height	759,967
Witness Tx's	1,811	Confirmations	11
Inputs	7,668	Miner	Binance Pool
Outputs	5,378	Coinbase	▓binance/790 ▓5▓W5>Dz>mmA▓▓▓whGpt;▓▓fhX▓J {Z▓8z:C]t>-▓?▓▓▓▓▓▓▓▓▓▓q▓▓r▓▓▓
Fees	0.03822393 BTC		
Fees Kb	0.0000264 BTC		
Fees kWU	0.0000096 BTC		
Fee Range	1-152 sat/vByte		
Average Fee	0.00001714		
Median Fee	0.00000624		

Figure 2.20. Details of a bitcoin block #759,967 are marked in Figure 2.19 with a red box (Blockchain.com, n.d.)

A block includes the block number, previous and current blocks' hash values, a timestamp, a nonce value, Merkle root hash value, the difficulty target value (Rajasekaran et al., 2022), and more details which can be seen in Figure 2.20. The hash value can be thought of as a unique digital fingerprint of the added value to the block. Any alteration in the data leads to an automatic change in the hash value, and the chain will be disrupted. In other words, it is impossible to change data in one block or remove any block from the BC without invalidating later blocks (Xiao et al., 2020). The impossibility of removing any appended block from the BC is called BC finality. The difficulty of forming the same chain again is the underlying factor for data immutability in BC. BC records are protected against attacks thanks to the under 51% rule (Chen et al., 2021). Therefore, a permanent record of data is possible with BC technology. Documents and entries stored in blocks are open to anyone and can be checked at any time to establish data validity (Yildizbasi, 2021).

Both the background process of peer-to-peer transactions and the addition of a new block to the existing BC environment are illustrated in Figure 2.21. Miners collect unconcluded transaction requests, and subsequently, they guess an arbitrary number called a nonce to solve the cryptographic puzzle. When the puzzle is solved, a new block will be generated and sent to the network for other nodes' approval. If other nodes verify the new block, it will be added to the BC, and all nodes on the web will also add the block to their copy of the BC (Raj, 2021).

There is a similarity between the Internet and BC. The Internet is a medium for the digital flow of information, and BC is a medium for the digital exchange of value units. BC is a digitally distributed network and ledger, which makes it possible to transfer assets securely without any central authority. The value transferred can be tokenized currency, land title, votes, and so on (Aggarwal & Kumar, 2021).

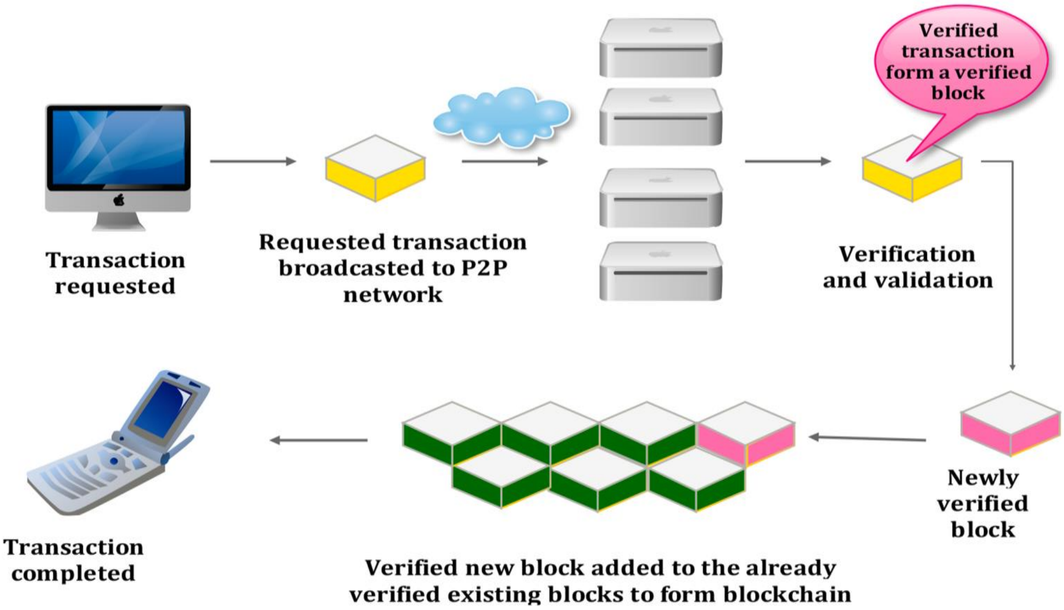

Figure 2.21. Transaction flow in the BC network (Rajasekaran et al., 2022)

The origin of BC is financial circles and passing through the business environment (Raj, 2021). Similarly, there is an established view regarding BC's usage areas' mainly finance and cryptocurrency. However, the only thing to record via BC technology is not cryptocurrency transactions (Mahmoud et al., 2019); it is possible to expand the use of BC in several industries such as supply chain, energy management, healthcare, asset tracking, the Internet of Things and smart building (Zarrin et al., 2021).

2.2.4 Classification of Blockchain Types

The type of BC is important in terms of the BC's context (e.g., structure and working way of BC network) and utilization. In other words, the level of transparency and centrality of the BC is affected by the permission type and related access and modification rights on the data in the BC (Böckel et al., 2021).

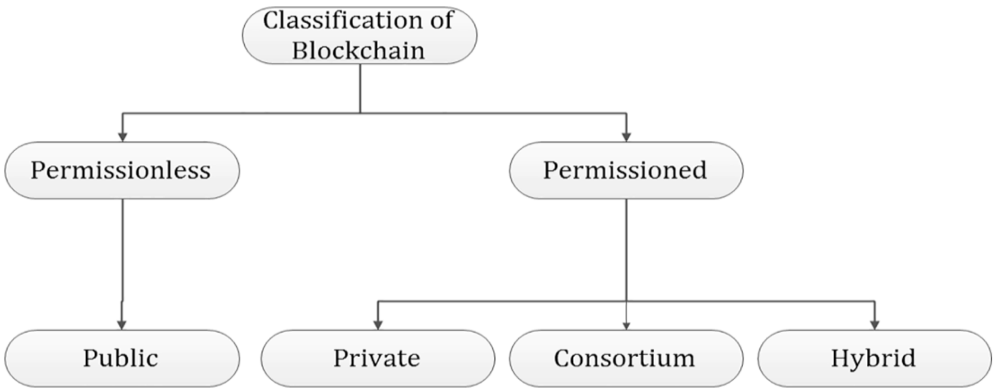

Figure 2.22. Classification of BC types (Rajasekaran et al., 2022)

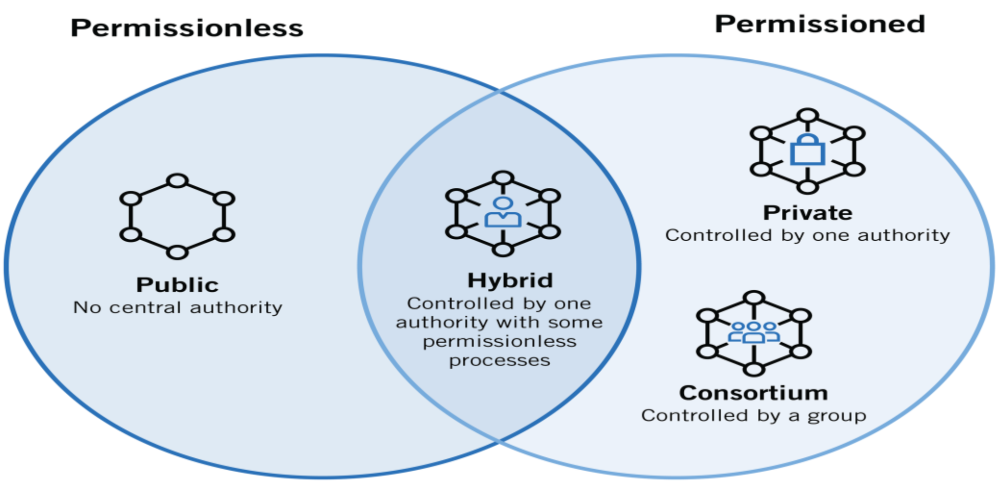

Figure 2.23. Classification of BC types (Wegrzyn & Wang, 2021)

As can be seen in Figure 2.22 and Figure 2.23, BC is classified into two main parts, which are permissionless BC and permissioned BC. Public and private blockchains differentiate in terms of who is allowed to participate in the network, control the consensus protocol, and manage the shared ledger (Jayachandran, Praveen, 2017). The differences and similarities between these two are listed in Table 2.2.

Table 2.2. Comparing permissionless/permissioned blockchains (Xiao et al., 2020)

Compared Topics and Explanations	
Governance	While permissionless BC can be governed publicly, permissioned one can be governed by a private authority or a consortium.
Participation	In permissionless BC, it is free to join and leave the network. However, the permissioned one requires authorization.
Node Identity	While the node identity is pseudonymous in permissionless BC, it is revealed in the permissioned one.
Transparency	The permissionless BC is open to transparency, while the permissioned one may be both closed or open in this regard.
Network Size	While permissionless BC has a large (thousands or more members) network size, the permissioned one has a small (tens-hundreds members) network size.
Network Connectivity	Permissionless BC has a low level of network connectivity, and the permissioned one has high network connectivity (mostly fully connected).
Network Synchrony	While permissionless BC has asynchronous / partially synchronous networks, the permissoned one has partially synchronous/synchronous networks.
Transaction Capacity	In permissionless BC transaction capacity is at a low level (ten-tens) and in permissoned one, it is at a high level (oft. thousands).
Application Examples	Some application examples for permissionless BC are cryptocurrency, smart contracts, public records, and Dapp. In addition, some application examples for permissioned BC are inter-bank clearing, business contracts, and supply chains.

2.2.4.1 Public Blockchain

Joining the public BC and using BC functions are open to everybody (Raj, 2021). Anyone can reach and participate in the network. Participants can join and quit the network at any time without any approval or permission as long as they have a valid account address (Rajasekaran et al., 2022 and Xiao et al., 2020). These types of blockchains are fully decentralized (Du & Li, 2022). There is no prerequisite to have a previous connection with the ledger or to have permission to join the BC network (Raj, 2021).

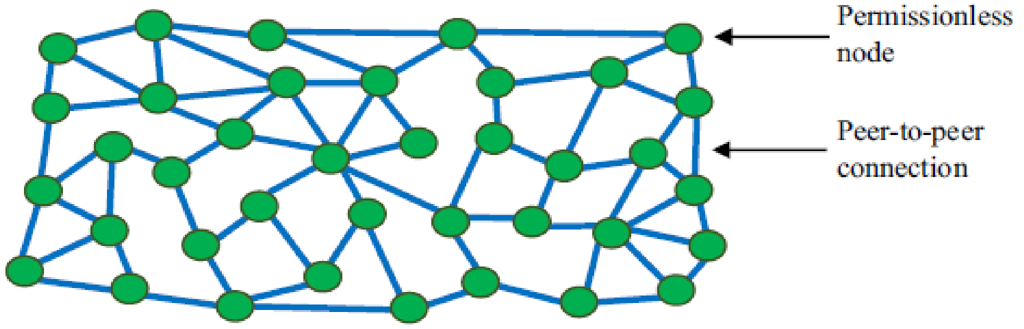

Figure 2.24. Representation of public BC network (Perera et al., 2020)

The blocks are publicly visible. Since a copy of the BC is distributed to other users, in case of any alteration in the data can be detected easily using other copies of blocks (Rajasekaran et al., 2022). Despite being a participant in BC networks, voting power directly relates to one's network resource possessions like storage space, token wealth, and computation power (Xiao et al., 2020). Similarly, the financial return from BC is directly proportional to the contribution to the consensus process (Du & Li, 2022). The purpose of the public BC mechanism is to increase the number of participants in the BC and nodes taking place in the consensus process as much as possible. Thus, as participation in the network increases, the number of nodes having a copy of the BC will also rise. As a result, the security of the network will be guaranteed automatically. However, despite storing the data using a hash mechanism and distributing it to all nodes in the network for security, public institutions, organizations, and companies may consider using public BC and storing their confidential data on the network risky. Keepers may break or leak the keys (Usta & Doğantekin, 2018). In this situation, a private BC form can be utilized to not share confidential data with all networks.

2.2.4.2 Private Blockchain

Its application scale is smaller when it is compared to the public BC. It can be used in a company or a smaller organization. A permission management component is needed to authorize participants within the system in private blockchains (Xu et al., 2016). Only authorized, permitted nodes can access to BC network and the recorded data on the BC (Rajasekaran et al., 2022). However, every node entered into the network has to obey the rules of the consensus protocol.

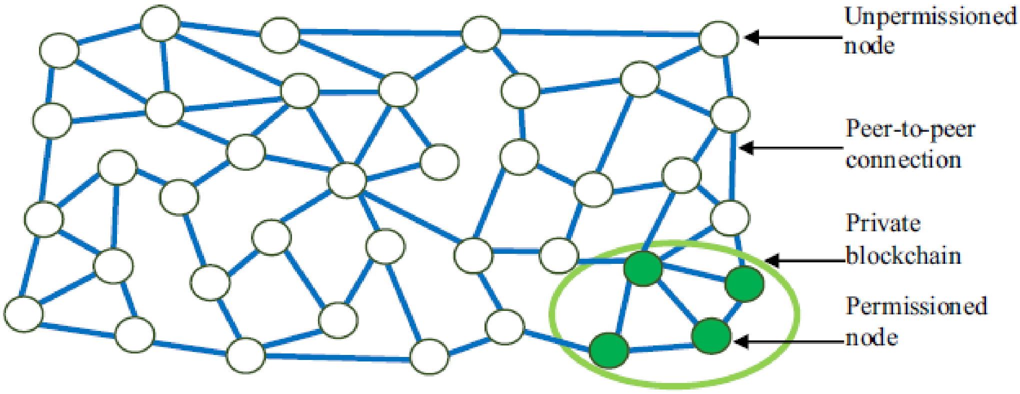

Figure 2.25. Representation of private BC network (Perera et al., 2020)

The entrance into the private BC is realized with an invitation. Thus, a safe data record environment is established between the network participants (Usta & Doğantekin, 2018). In Figure 2.26, the laptop operates as a mining node, and the RPI 3b+ runs as a normal node that shares data. The creation of a block is very fast, thanks to the permission criterion limiting access to the BC networks. Additionally, the transactions cannot be seen by all nodes in the network, only permitted nodes can see them. Identifying any node engaged in the transaction is easier. Since the number of nodes permitted to make transactions is limited, despite the enlargement of the network, the speed and efficiency of BC are not affected by this situation. The structure of private BC is centralized (Rajasekaran et al., 2022), therefore opposite to the original emergence aim of the BC concept.

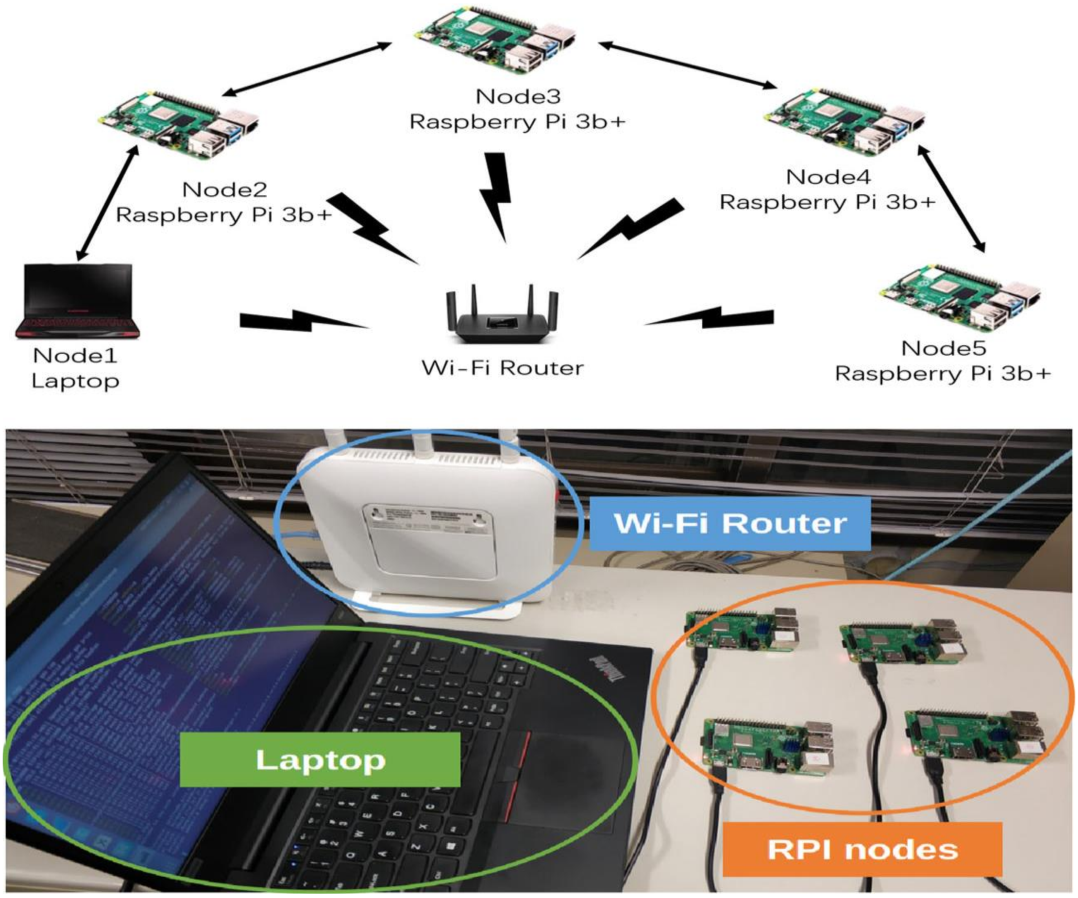

Figure 2.26. An exemplary scheme of a private BC (Chen et al., 2021)

In a private BC system, it is possible to permit only the related nodes to access recorded data. Additionally, the private BC makes it available to include only the selected parties in the consensus process among the permitted node. As a result, a multi-layer and secure data record environment is formed between the included parties (Usta & Doğantekin, 2018).

2.2.4.3 Consortium Blockchain

As seen in Figure 2.23, consortium blockchains are a kind of private blockchains (permissioned), but there is no single owner. Consortium blockchains, or as mentioned in the literature, federated blockchains, are managed by more than one organization (Voshmgir & Kalinov, 2017). Consortium blockchains make it possible for participants to complete some important, confidential works privately while other works remain publicly visible (Rajasekaran et al., 2022). Organizations can prepare their way of communication and can make the desired data visible to related participants (Perera et al., 2020). Mostly, the banking sector is using consortium BC. Preselected sets of nodes supervise the consortium BC consensus protocols (Voshmgir & Kalinov, 2017).

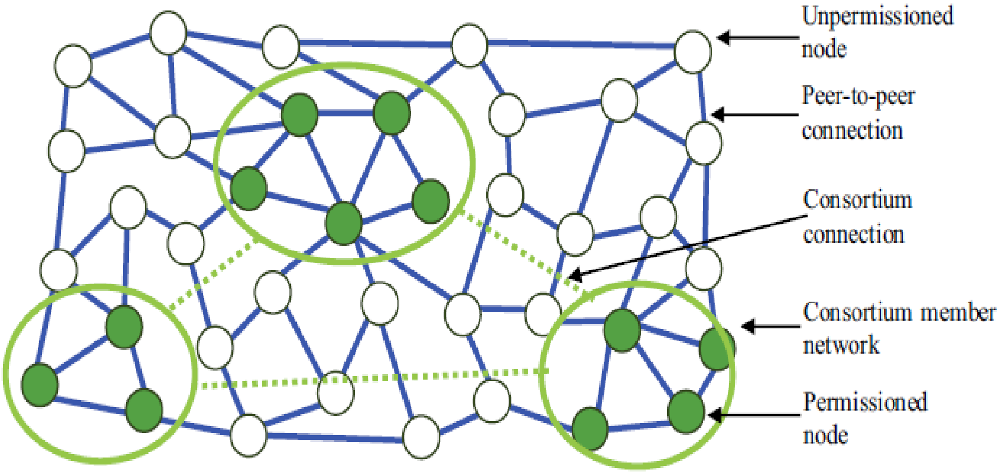

Figure 2.27. Representation of consortium BC network (Perera et al., 2020)

One should be a member of any of the consortium members' networks to access the ledger. Therefore, the consortium BC is also permissioned (Rajasekaran et al., 2022). Additionally, a consortium BC can determine each node's access level to the information in the ledger (Perera et al., 2020).

Table 2.3 includes the public, private, and consortium blockchain comparison.

Table 2.3. Comparing public/private, consortium blockchains (Zheng et al., 2017)

Property	Public Blockchain	Consortium Blockchain	Private Blockchain
Consensus	All miners	Selected set of nodes	One organization
Read permission	Public	Could be public or restricted	Could be public or restricted
Immutability	Nearly impossible to tamper	Could be tampered	Could be tampered
Efficiency	Low	High	High
Centralized	No	Partial	Yes
Consensus process	Permissionless	Permissioned	Permissioned

2.2.4.4 Hybrid Blockchain

As seen in Figure 2.23, hybrid blockchains are located at the intersection of permissionless and permissioned blockchains. The hybrid BC is close to the consortium BC, but the hybrid BC integrates the best features of both blockchains. The scalability of a hybrid BC is better since the verification of transactions is distributed to a group of authorized nodes (Rajasekaran et al., 2022).

2.2.4.5 Summary of Blockchain Section

To sum up, BC is a distributed system. It provides a stable service to nodes that do not completely trust each other. In general terms, the transactions are gathered by nodes to build a block encrypted via public key, message authentication codes, signatures, and hashing algorithm to supply adequate security. Subsequently, the approved block is joined to the chain after the verification process, and the transaction is completed. Mentioned topics about the BC network are executed within the borders of the consensus protocol on which all nodes agree. All these works can be completed without any intermediary third party within the BC network. In addition, all these works can be completed dependably and securely (Qiu et al., 2022).

2.2.5 Application Domains of Blockchain Technology

Based on the successful use of this new tech in the cryptocurrency environment, some other sector leaders also asked about the usability of BC technology in their sector. One other factor positively affecting the diffusion of BC into other sectors is BC's inherent relation to monetary issues. As a result, its usage gradually spread to other domains or sectors. Several studies were examined to investigate BC application areas in the literature. As seen in Figure 2.28 and Figure 2.29 BC has various usage areas.

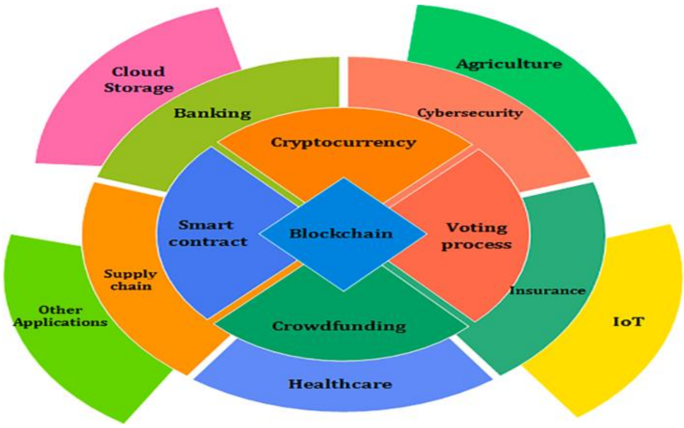

Figure 2.28. BC application areas (Rajasekaran et al., 2022)

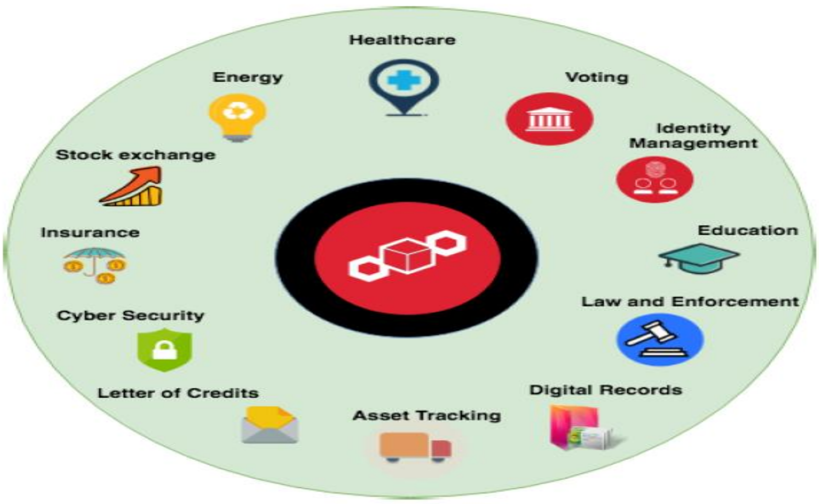

Figure 2.29. Application areas of the BC (Monrat et al., 2019)

2.3 Circular Economy and Blockchain Intersection

Both CE and BC are new concepts and are frequently mentioned as different bodies in the literature. Keeping materials and products within productive use as much as possible in a CE-based system is crucial. In a CE ecosystem materials and products are efficiently looped back into the value chain upon their end of use; this promotes the reduction and elimination of waste (Erol et al., 2022).

However, forming business models based on CE will require systemic changes and numerous obstacles to overcome (Ritzen & Sandstrom, 2017). Material flow, traceability, and collaboration among suppliers are particularly crucial in accelerating CE adoption (Erol et al., 2022). Similarly, the main obstacles to a circular economy include financial constraints, such as high investment prices and linear lock-ins, and a lack of technology options (De Jesus & Mendonca, 2018).

Additionally, several conditions must be satisfied to mainstream the CE and overcome obstacles, including the design and production of circular products, new business models, the ability to reverse cycles to recycle or reuse materials, and underlying system conditions. The needed underlying system conditions are fundamentally related to technological fields providing information sharing and collaboration infrastructure (Böckel et al., 2021).

As a disruptive technology, BC is a distributed platform that can lessen the effects of challenges towards the proper adoption of the circular economy (Erol et al., 2022). BC technology can satisfy the needed information technology infrastructure for the successful implementation of the CE (Böckel et al., 2021).

Moreover, BC has the advantages of decentralization, fault tolerance, cryptographic security, data integrity, and authentication, which are essential to the CE's digital transition. In short, the blockchainification of CE might make specific implementation-related difficulties easier since it assures data ownership, data sharing, transparency, privacy, and property rights between competitors (Kumar & Chopra, 2022).

On the other hand, the blockchainification of CE also brings some barriers affecting its practicality and scalability. The barriers to a BC-based CE include policy and regulatory challenges, cultural and organizational challenges, consensus and smart contract-related challenges, scalability issues, data management, data storage capacity, data anonymity, data privacy, security, financial challenges, and finally, lack of skilled workforce regarding this new concept (Kumar & Chopra, 2022).

2.4 Integrating Blockchain and Circular Economy in the Construction Industry

According to the literature, for mainstreaming CE, a number of conditions need to be met, including designing and producing circular products, developing new business models, reversing cycles, and ensuring that the underlying systems are in place to facilitate recycling and reusing materials (Böckel et al., 2021). The needed underlying systems are fundamentally related to technical fields that supply a platform for collecting, storing, sharing, protecting, and managing information and providing secure collaboration. Literature suggests that BC technology can provide this necessary underlying information technology infrastructure for the CE's successful implementation. It is understood from this perspective that BC is a promising technology that can be used beneficially in managing information or data-related topics (CE-related data) for the successful usage of the CE in CI.

CE tries to preserve the utility and value of any component or product. BC technology helps this process by providing data related to any building component's provenance or current situation. The predictive maintenance or recovery process can be executed based on these data. As a result, any disruption in the structure's functionality can be prevented.

CE aims to minimize waste; therefore, reusing building materials from all fields of any building is a requirement of CE adoption in CI. Connectedly, a database including all recovered or reusable construction materials can be beneficial in successfully using CE in CI. The BC has a critical role in this scenario. The data management in the database can be executed more easily and securely with the integration of BC in the process.

In addition, CE requires traction, ownership, and waste responsibility. In the linear economy model, ownership and waste responsibility are also transferred when any product is sold to any consumer or user. CE tries to track all participants' responsibilities through any product's life cycle process, starting from the initial to the final. In the construction context, when any building, building-related material, or component is sold to other users, CE aims to track the ownership, roles, and liabilities (e.g., the carbon footprint of any product) of all responsible parties through the entire life cycle process of the mentioned value. For example, the root responsibility should be tracked if any component includes any toxic ingredient from its production process. BC technology helps with this tracking process by providing data security, privacy, immutability, and transparency. The use of BC increases the end users' knowledge about the construction or production process of any material or structure. BC also may help in the management of supply chain data of CI transactions.

Moreover, technological developments in the construction industry (e.g., RFID technology, 3D printers, BIM, digital twins, automation, and robotics) also facilitate the adoption of BC and CE in the industry. These technologies help to create or collect data from the buildings or their components. Hence, as the technological developments diffuse in the CI more, the amount of data generated through the CI-related processes increases (e.g., data in BIM projects, planning software, procurement data, raw material data, data related to the current situation of buildings and building materials).

Besides, the diffusion of fabrication and modularization concepts in the CI increased the capability of constructors to trace all processes in detail, from the provenance of resources to the end user and the current situation of final products or building materials. In addition to the mentioned processes, BIM models of the structures also generate data (e.g., heat capacity, thickness, weight, strength, and volume). As a result, a vast amount of data is generated in CI. Based on this vast amount of data production, some data-related problems arise. For example, confidentiality, security, storage, and data transparency are some of them. Moreover, issues related to trust, data ownership, data sharing mechanism, and property rights are additional problems.

As a response to all these problems mentioned above, integrating BC into the CI provides some solutions. BC provides inclusive, transparent, reliable material and information traceability regarding materials' current state and provenance. Additionally, BC provides cryptographic security, privacy, and immutability, in a decentralized environment. It includes smart contracts and provides the infrastructure for automation. As a result of mentioned properties, it forms trust between competing CI participants.

Yang et al. (2020) stated that Ethereum, Hyperledger Fabric, and R3's Corda are the three main blockchain platforms. Hyperledger Fabric and Ethereum can be used in any domain while R3's Corda is suitable only for financial use purposes. Accordingly, Ethereum and Hyperledger Fabric platforms can be utilized in the construction domain. In addition to being one of the most mature blockchain platforms, Hyperledger Fabric is the first to enable the execution of smart contracts in several general-purpose programming languages (e.g., Node.js, Java, and Go). Additionally, Ethereum introduced the smart contract concept to the literature and smart contracts form the core of the applicability of BC in CI. It uses the PoS consensus mechanism and is suitable for both public and private BC applications. The commonly used script language in Ethereum is Solidity for smart contract coding. (Yang et al., 2020). The private BC may be selected if the company owner wants to keep the firm's data private from all participants. However, in that case, the original purpose of BC usage, which is openness to every participant, will be damaged, and a trusted third-party, entity comes again.

As an alternative, the public BC will be selected, and all data will be opened to all participants. If there is private information belonging to the firm, the owner may hesitate to use this type of BC. In that case, the hybrid BC, which is a combination of private and public ones, may be a solution. In the hybrid blockchain, certain individuals within the company can determine which transaction will be public and which will be limited to a small group of members.

From a broader perspective, the number of studies regarding the integration of BC-enabled CE in the CI is very limited in the literature. Additionally, the existing studies in the literature focused on narrow topics like construction and demolition waste, construction supply chain, usage with digital twins, and plastic waste recycling. Therefore, the literature lacks a general view of BC and CE-adopted CI. As it was mentioned in the previous section, individual and joint adoption of CE and BC in a general perspective has various enablers and barriers/challenges without particular to any sector.

Although the CE and BC were associated individually with the CI, their collocated usage in the CI lacks in the literature. The relation between the CI, BC, and CE based on the studies in the literature can be seen in Figure 2.30. This figure is prepared by using VOSviewer software. Blockchain and construction related 205 studies' titles were used as input. The separated position of the circular economy can be seen easily.

The mentioned challenges in the literature can be summarized as follows; political/governmental challenges, economic challenges, social challenges, technological challenges, data-related challenges, BC performance challenges, lifecycle complexity challenges, environmental challenges, standards and compliance challenges, and finally, organizational challenges. These challenges have been investigated within the scope of this study.

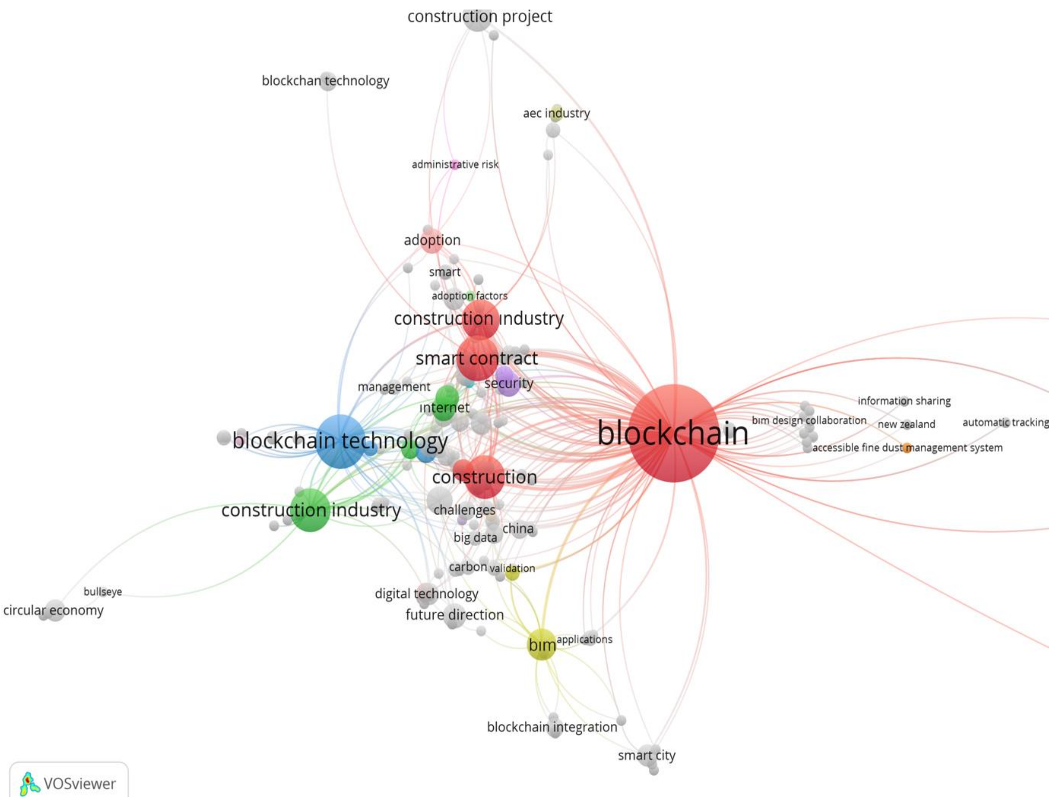

Figure 2.30. General view of BC, CI and CE studies in literature

When it comes to the enablers collected from the literature, the list can be summarized as follows. Using blockchain brings enhanced cryptographic security, data integrity and authentication, data ownership, data sharing, transparency, privacy, and property rights, increasing the trust between the CI's competing participants (Hunhevicz & Hall, 2020 and Shojaei et al., 2021). Improved communication, innovative business models, new regulations and incentives, and educating industry stakeholders can be added to the list of enablers/drivers. Moreover, there is a possibility of increasing competitive advantage for construction firms in the case of adopting CE and BC technologies.

These enablers and barriers affect the adoption behavior of CI participants. Therefore, understanding and being aware of these enablers and barriers is a critical issue in the adoption of CE and BC in the CI. If the CI participants are aware of the BC and CE concepts, they would think about how they could adopt these concepts in their works, and so they would investigate the enablers and barriers of adoption.

A detailed investigation of awareness levels of CE and BC concepts in the construction sector, as well as their enablers and barriers to adoption in that industry, has not been conducted.

Therefore, the objective of this study is to fill that gap. Additionally, the enablers and barriers, which were not identified in the CI literature, are associated with the construction field within the scope of this study. The approach and methodology are explained in the next chapter.

CHAPTER 3

METHODOLOGY

In the previous chapter, a comprehensive literature review study was carried out on BC, CE, and their usage in the CI. The CE and BC are explained in detail. Next, brief information is given about the application domain of BC technology, including the CI. Finally, the position of BC and CE integration into the CI in the literature is depicted. The need for identifying the enablers and barriers of CE and BC in the CI is presented. This chapter explains the design of the methodology based on the literature review and the survey study.

3.1 Details of the Methodology

This research examines the factors challenging and enabling the transition to the BC and CE-adopted CI. To understand this transition process in detail, the importance of factors (enablers and barriers) retrieved from the literature was requested to be evaluated by professionals in the CI and several construction-related sectors.

The thesis methodology includes seven steps. The roadmap of the methodology can be seen in Figure 3.1.

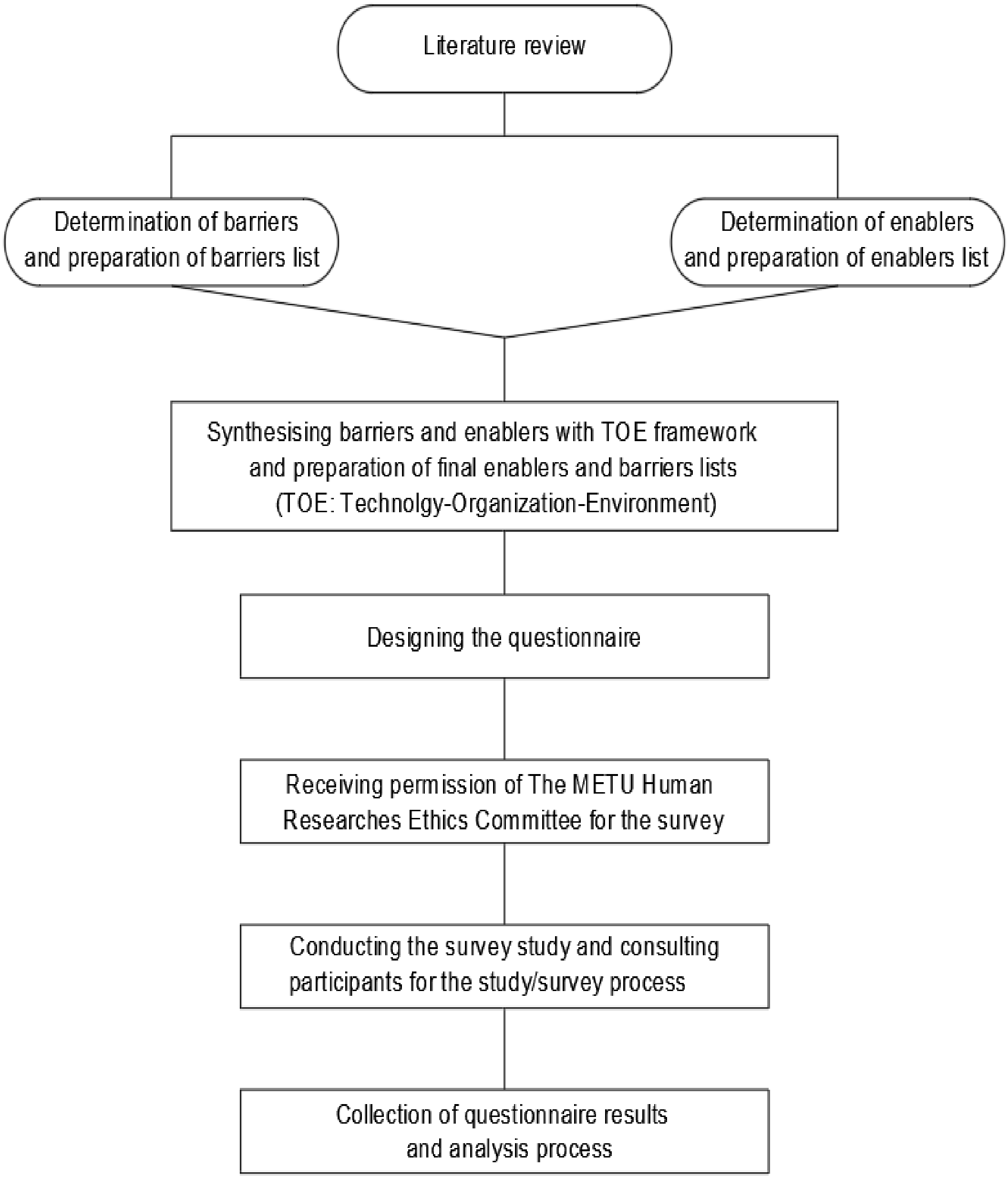

Figure 3.1. Methodology Roadmap

3.1.1 Determination and Categorization of Barriers and Enablers

This section explains the details of Step 1, Step 2, and Step 3, which are about determining and categorizing enablers/barriers, and preparing the final enabler and barrier lists.

Step 1: The literature was reviewed to determine enablers and barriers of both CE and BC technology usage in general and, in particular, to the CI.

Step 2: The lists of specified barriers and enablers were prepared. Gathered barriers from the literature were named sub-barriers. Next, sub-barriers were grouped into categories of barriers.

Step 3: Since enablers and barriers must be identified and categorized systematically, the developed lists of barriers and enablers were synthesized regarding the Technology- Organization-Environment (TOE) framework (Oliveira & Martins, 2010). As a result of this process, the final lists of enablers and barriers were prepared.

3.1.1.1 Details of Literature Search Process

The details of the literature search process are demonstrated in Figure 3.2. The literature review process was carried out by searching the predetermined words in the web of science database. The keywords searched for were "*circularity*," "*sustainability*," "*blockchain,*" "*construction,*" and "*building*" *terms*. To reach these words and not miss any related study, the root words of "*sustainability*" and "*circularity,*" which are "*sustain*" and "*circular,*" were examined. The "*sustain,*" "*circular,*" and "*blockchain*" words were accepted as the backbone words of the research, and the terms related to "*construction*" and "*building*" was derived through the search process. The derived words for "*construction*" and "*building*" are the words "*build,*" "*AEC,*" "*built,*" "*architect,*" "*struct*,*" "*house,*" "*home,*" "*facil*",* "*site,*" "*assembly,*" "*civil,*" "*modular.*"

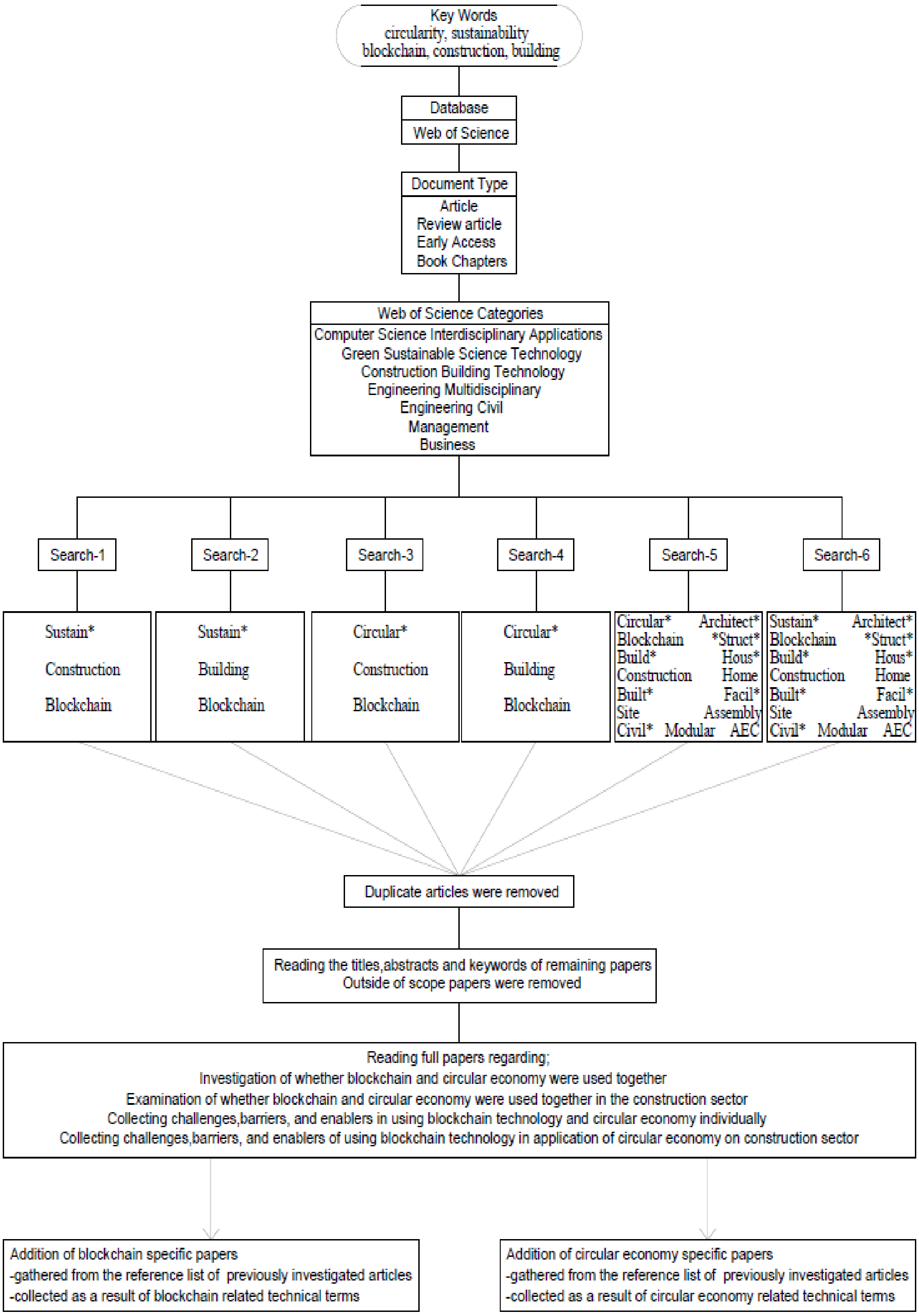

Figure 3.2. Literature review process

Additionally, if they were related to the thesis topic, some articles from the references list of the investigated articles were also included in the study. During this process, many original websites and many other search engines like Mendeley, Scopus, and Google Scholar were also utilized. The search steps and queries written to the web of science search engine are explained below.

Search 1: Sustain*, construction, and blockchain terms are searched. The following formula was entered into the web of science database to examine mentioned words together.

"*Sustain* (Topic) AND construction (Topic) AND blockchain (Topic) and Article or Review Article or Early Access (Document Types) and Construction Building Technology or Computer Science Information Systems or Engineering Civil or Green Sustainable Science Technology or Computer Science Interdisciplinary Applications or Engineering Multidisciplinary or Business (Web of Science Categories)*"

Search 2: Sustain*, building, and blockchain terms are searched. The following formula was entered into the web of science database to examine mentioned words together.

"*Sustain* (Topic) AND building (Topic) AND blockchain (Topic) and Article or Review Article or Early Access (Document Types) and Green Sustainable Science Technology or Business or Management or Computer Science Interdisciplinary Applications or Engineering Civil or Construction Building Technology or Engineering Multidisciplinary (Web of Science Categories)*"

Search 3: Circular*, construction, and blockchain terms are searched. The following formula was entered into the web of science database to examine mentioned words together.

"*Circular* (Topic) AND construction (Topic) AND blockchain (Topic) and Article or Review Article or Early Access (Document Types) and Construction Building Technology or Engineering Civil or Green Sustainable Science Technology or Management (Web of Science Categories)*"

Search 4: Circular*, building, and blockchain terms are searched. The following formula was entered into the web of science database to examine mentioned words together.

"*Circular* (Topic) AND building (Topic) AND blockchain (Topic) and Article or Review Article or Early Access (Document Types) and Green Sustainable Science Technology or Management or Engineering Civil or Construction Building Technology or Engineering Multidisciplinary or Business or Computer Science Interdisciplinary Applications (Web of Science Categories)*"

Search 5: The following formula was entered into the web of science database to examine the words mentioned together.

"*circular* blockchain construction (Topic) OR circular* blockchain build* (Topic) OR circular* blockchain AEC (Topic) OR circular* blockchain built* (Topic) OR circular* blockchain architect* (Topic) OR circular* blockchain *struct* (Topic) OR circular* blockchain hous* (Topic) OR circular* blockchain home (Topic) OR circular* blockchain facil* (Topic) OR circular* blockchain site (Topic) OR circular* blockchain assembly (Topic) OR circular* blockchain civil* (Topic) OR circular* blockchain modular (Topic) and Article or Early Access or Review Article (Document Types) and Green Sustainable Science Technology or Management or Business or Computer Science Interdisciplinary Applications or Construction Building Technology or Engineering Civil or Engineering Multidisciplinary (Web of Science Categories)*"

Search 6: The following formula was entered into the web of science database to examine the words mentioned together.

"*sustain* blockchain construction (Topic) OR sustain* blockchain build* (Topic) OR sustain* blockchain AEC (Topic) OR sustain* blockchain built* (Topic) OR sustain* blockchain architect* (Topic) OR sustain* blockchain *structur* (Topic) OR sustain* blockchain hous* (Topic) OR sustain* blockchain home (Topic) OR sustain* blockchain facil* (Topic) OR sustain* blockchain site (Topic) OR sustain* blockchain modular (Topic) OR sustain* blockchain assembly (Topic) OR sustain* blockchain civil* (Topic) and Article or Review Article or Early Access (Document Types) and Green Sustainable Science Technology or Management or Business or Computer Science Interdisciplinary Applications or Construction Building Technology or Engineering Civil or Engineering Multidisciplinary (Web of Science Categories)*"

3.1.1.2 Details of TOE Framework

The TOE (Technology-Organization-Environment) framework was formed by Louis G. Tornatzky and Mitchell Fleischer in 1990 (Oliveira & Martins, 2010). According to the TOE framework, three particular determinants affect the adoption of any technology in an organization (Baker, 2010). To illustrate, technological, organizational, and environmental factors determine the adoption and implementation dynamics of technological innovation in a business. In the technological context, both internal and external technologies are considered, including current applications and equipment within the company, as well as external technologies available. An organization's context includes measures such as its scope, size, and management structure. An organization's environmental context can be defined as the environment in which it operates, the industry in which it runs, its competitors, and what deals it has with the government (Oliveira & Martins, 2010).

The TOE model was used to demonstrate the adoption of electronic data networking, e-business inter-organizational systems, and open enterprise systems. Manufacturing, health care, retail, wholesale, and financial services have all used the TOE model to explain innovation adoption. Technological changes, organizational changes, and environmental changes all influence the way an organization identifies, searches for, and adopts new technology (Baker, 2010). Therefore, the TOE framework was used as a systematic way in this study to classify the barriers and enablers (adoption factors) of blockchain and CE adoption.

3.1.2 Survey Study

This section gives brief information about the remaining part of the thesis in 4 steps: Step 4, Step 5 and Step 6, and Step 7. These steps contain the preparation, and application process of the survey study, the structure of the conducted survey, and the analysis of survey results.

Step 4: A survey was conducted to determine the importance of each predetermined barrier and enabler in the transition to the BC and CE-adopted CI. A survey was conducted by using final lists of enablers and barriers. The survey preparation process includes the following steps.

- Initially, a survey draft was designed and proposed to three professionals to receive feedback regarding the content and cohesion of the survey draft.
- Based on the comments, the needed editions were completed, and the final form of the survey was prepared.

The targeted set of participants includes experienced persons in the CI and construction-related sectors, such as academicians, engineers, architects, and consultants. In the first step of the survey, the participants were asked to enumerate their personal opinions using a 0 to 5 Likert scale regarding the importance of each barrier and enabler in the transition to the BC and CE-adopted CI. In the second part of the survey, the aim is to evaluate the effects of the main enablers on the main barriers listed in the literature. The participants were asked to share their personal views using a 0 to 5 Likert scale regarding at which level the enablers in the literature alleviate the barriers regarding the transition to the BC-supported CE. As a result, the survey's final results were presented using descriptive statistics.

Step 5: The permission of the METU Human Researches Ethics Committee was received for the survey study (Permission protocol number: 0097-ODTUİAEK-2023).

Step 6: The survey was distributed to the professionals as a connection link via E-mail, LinkedIn, WhatsApp, SMS, and Instagram platforms.

Step 7: The survey results were collected via the previously sent link. Then the survey results were analyzed and discussed.

In this chapter, the design of the methodology was explained based on the literature review and the survey study. The methodology used in the thesis and the survey details were explained. In addition, the properties of the TOE framework and its usage areas were examined.

The next chapter demonstrates the literature review findings completed within the rules mentioned in this chapter, the findings of the survey study and the discussion of the findings.

CHAPTER 4

FINDINGS

This chapter includes the results of the literature review and survey study on the enablers and barriers of blockchain and circular economy within the construction industry. First, this chapter categorizes these enablers and barriers according to the TOE framework. Then, this chapter presents the conducted survey findings and related discussions.

4.1 Enablers and Barriers

4.1.1 Barriers

Synthesized barriers are categorized according to the TOE framework. Firstly, the technological context is handled. Within the technological context, 45 sub-barriers are grouped under 11 barriers. The prepared lists also depict the scope of the technological barriers (whether the barrier is only related to CE adoption, BC adoption, or both). The barriers in the technological context are as follows; responding capacity-related challenges, business use case challenges, existing infrastructure-related challenges, BC limitations and requirements-related challenges, data-related issues, traceability, transparency, and immutability issues, BC compatibility, availability, and interoperability challenges, BC complexity related challenges, ownership and liability issues, contractual uncertainty issues, BIM and BC integration challenges. For detailed lists and more information about sub-barriers, please see Appendix A.

Secondly, the organizational context is examined. Within the organizational context, 30 sub-barriers are grouped under 5 barriers. The prepared lists also include the scope of the organizational barriers (whether the barrier is only related to CE adoption, BC adoption, or both). The barriers in the organizational context are as follows; operational and supply chain risks which companies may face during the adoption process, inertia in businesses to proposed changes, financial resources-related issues, lack of awareness and low participation of company members’ commitment to change, lack of organizational and business model readiness. For detailed lists and more information about sub-barriers, please see Appendix A.

Thirdly, the environmental context is investigated. Within the environmental context, 47 sub-barriers are grouped under 13 barriers. The prepared lists also include the scope of the environmental barriers (whether the barrier is only related to CE adoption, BC adoption, or both). The barriers in the environmental context are as follows; uncertain and insufficient regulations, lack of know-how/proper vision and incentives, lack of supply chain support, sustainability vs. profit paradox, lack of awareness and understanding regarding BC and CE, resistance to change, lack of community support and customer readiness, CI characteristics, the complexity of the recycling process, tracking difficulties of materials, the environmental and ecological burden of BC, standards and compliance issues. For detailed lists and more information about sub-barriers, please see Appendix A.

4.1.2 Enablers

Synthesized enablers are categorized according to the TOE framework. Within the technological context, 17 enablers/drivers are listed. In addition, 7 enablers/drivers are listed in an organizational context. Finally, in the environmental context, 5 enablers/drivers are listed. The prepared lists also include the scope of the technological, organizational and environmental enablers (whether the enablers are only related to CE adoption, BC adoption, or both). For detailed lists and more information about enablers and drivers, please see Appendix A.

4.2 Enablers and Barriers

4.2.1 Responding Capacity

This barrier is about the ability, effectiveness, and feasibility (Huang et al., 2022) of CE and BC in solving CI-related problems. It refers to the possible insufficiency of BC's technological capabilities in ensuring data confidentiality, security, privacy, and so insufficiency in forming trust between different sector segments. Since they are new concepts, the immaturity and required time to be adopted appropriately (Chaudhuri, Subramanian, & Dora, 2022; Santana & Ribeiro, 2022) are fundamental challenges for both CE and BC implementation in the CI. This immaturity negatively affects the CE and BC's ability, effectiveness, and feasibility.

On the other hand, the ability and effectiveness of BC in adopting CE have also been examined in the literature as enablers/drivers for adoption. The details are presented under the following topics.

- The resilience of the BC network when one or more participants are unable to perform (Shojaei et al., 2021).
- Using BC eliminates the need for a trustable third party for all transactions and contributes to reducing transaction costs (Böhmecke-Schwafert et al., 2022 and Rejeb et al., 2022).
- Provided decentralized environment, disintermediation, immutability, enhanced security, and privacy build trust for the sector participants and increase interoperability (Rejeb et al., 2022).
- Due to the immutable, tamper-proof, and distributed data structure, responsible production regarding CE becomes possible (reduced harmful compounds and reduced emission levels) (Böhmecke-Schwafert et al., 2022).
- Smart contracts provide automation in contractual responsibilities and increase the trust between sector participants (Rejeb et al., 2022).

- Technological advancements in information sharing, collaboration, and feedback-rich systems contribute to BC and CE's increased responsiveness (Khan et al., 2022 and Rejeb et al., 2022).
- As big data and data analytics are used to create databases for reusable components, blockchain has become more usable in the construction industry for CE implementation (Cruz Rios et al., 2021 and Khan et al., 2022).
- Enhancements in the utilization of technologies such as BIM, process digitization, digital and 3D printing, the internet of things (IoT), automation, robotics, and Industry 4.0 in the construction sector increase the usefulness of BC in enabling CE adoption (Khan et al., 2022 and Rejeb et al., 2022).

4.2.2 Business Use Cases

RFID (Radio Frequency Identification) systems are tools used to identify objects individually using radio frequencies. In the CI, the use of this technology has been examined limitedly for tracking components. The sector includes a vast diversity of products, including concrete, aluminum, glass, wood, and water. RFID technology can be a good enabler in adopting the CE by making it capable of tracking the origin of any member or product used in the CI. Therefore, extending the use of RFID systems among supply chain partners and increasing the accuracy and effectiveness of the system is a need and a challenge (Santana & Ribeiro, 2022) for the successful adoption of the CE in the CI.

Additionally, tracking all construction activities is a challenging issue with RFID systems due to inherit properties of the industry. Despite its challenges in the adoption process, it should be noted that managing such a vast volume of product movement can be simplified and made manageable by utilizing BC technology in the CI activities. The BC platform can provide comprehensive, transparent, and reliable material traceability and information tracking regarding the materials' sources and their current state (Shojaei et al., 2021).

The CE requires the reuse of components, and most of the time, making building residuals reusable is challenging due to material recoverability and composition (Charef & Lu, 2021). In addition, technological challenges also exist to separate construction materials and recover them into the cycle again. Connectedly, difficulties in disassembly operations and safety (Erol, Ar, Peker, & Searcy, 2022; Dulia, Ali, Garshasbi, & Kabir, 2021) are important challenges for the adoption of the CE in the CI. Additionally, the existing buildings were not designed from the CE point of view.

4.2.3 Existing Infrastructure-Related Topics

Current systems may cause some barriers to the successful implementation of the CE and BC in general (Huang, Zhen, Wang, & Zhang, 2022; Magrini et al., 2021). To illustrate, adopting BC technology requires stable and fast internet access. In detail, the lack of existing technical infrastructure, bandwidth, and connectivity is a challenge for the adoption (Böhmecke-Schwafert et al., 2022). Thus, BC implementation in the supply chain faces challenges related to performance and scalability (Huang et al., 2022).

This situation is valid for all sectors. The CI participants use the same communication infrastructure with other sectors. Hence, this general barrier is also in effect for using BC and CE in the CI. As a result, there is a need to develop existing communication networks (Teisserenc & Sepasgozar, 2021). Connectedly, since BC is an infant technology, rapid and continuous developments are expected of it. Therefore, integrating BC with legacy systems is challenging due to its continuous development (Rejeb et al., 2022) until it matures. Connectedly, technology update is a necessary factor for a successful BC-enabled CE application regarding being able to access the data at any time (Charef & Lu, 2021).

4.2.4 Blockchain Limitations and Requirements-Related Challenges

Adopting BC highly requires computing equipment (Teisserenc & Sepasgozar, 2021) and high computing power. Additionally, BC technology requires specific IT (Information Technology) infrastructure that may affect supply chain members' adoption behaviour and intent to use (Kouhizadeh et al., 2020). Moreover, the limited storage capacity of BC is another challenge. Adopting a BC-supported CE requires the entry of data received through the life cycle of construction projects. Most of the time, the data collected from construction projects require a high storage capacity to be kept. However, due to the limited storage capacity of the BC, less critical data are stored out of the BC, while more critical data are anchored to the BC (Teisserenc & Sepasgozar, 2021). As a final comment, it has to be noted that the mentioned requirements are costly and need intensive investments.

4.2.5 Data-Related Issues

It is important to note that BC technology is still in its infancy, even though it shares information very securely and reliably. Popular BC applications have suffered from system failures and real-life attacks. As a result of these failures and attacks, various questions were raised about the susceptibility of BC in other business frameworks, including supply chains (Kouhizadeh et al., 2020). To illustrate, public blockchains in which a few individuals control most of the network's computing power are susceptible to attacks at 51%. Therefore, the possible insufficiency of BC in security, privacy, and tamper-proof data requirements for industries, including the CI, is a challenge for adoption. These data requirements are set because of the sensitive content of information stored in the BC (e.g., companies' customer information) (Rejeb et al., 2022).

In addition, data reliability, accessibility, availability, and management are essential factors for the acceptance and use of sustainable approaches in construction (Charef & Lu, 2021). However, false and incomplete data entry in the BC environment causes issues in the authentication and trustworthiness of the data (Teisserenc & Sepasgozar, 2021). The nature of the CI is prone to such false or incomplete data entry.

The false information entry problem in the BC is the only challenge that has been debated more in practice than in research and has been addressed more frequently in practice. Therefore, an outside validation and certification process is necessary (Böckel et al., 2021) for a successful BC-enabled CE.

4.2.6 Traceability and Transparency Issues

The construction supply chain lacks transparency and traceability due to the high number of sector participants and short periods. Therefore, shifting CI through the CE model requires traceability, visibility, and transparency of information and components (Teisserenc & Sepasgozar, 2021). By providing a decentralized platform, BC technology enhances supply chain transparency and empowers firms to move towards the CE model. However, although BC aims to anonymize users' identities through digital signatures, transactional security via cryptography stays as a challenge.

In addition, data privacy issues can arise in BC-based inter-firm data management and control contexts. Information belonging to company assets and resources may be considered confidential and sensitive. Therefore, sharing data via BC can be a risk (Rejeb et al., 2022). In other words, BC can increase transparency and solve the problem of supply chain traceability. Still, it can also share crucial information that companies may be hesitant to share with others. Sharing information transparently for sustainability poses a severe conflict with the protection of company know-how and intellectual property rights. Similarly, transparent information sharing leads firms to lose their competitive advantage. For instance, some businesses might not want to share specific sustainability performance data and methodologies (Kouhizadeh et al., 2020).

Therefore, there is resistance to a high level of transparency among supply chain actors; for example, product content transparency is a critical issue for implementing CE to see the properties of the products (Charef & Lu, 2021). However, firms may not volunteer to share that product's content. As a result, the determination of an appropriate level of transparency within a network of parties is a critical challenge in the use of BC for the CE. (Kouhizadeh, Zhu, & Sarkis, 2020; Wang, Singgih, Wang, & Rit, 2019). This situation is valid for CI companies as well.

4.2.7 Blockchain Compatibility, Availability, and Interoperability Challenges

Under this topic, some areas where BC application in the CE has shortfalls are discussed item by item. All challenges mentioned below can be faced when BC technology is applied in CI.

-The tools and applications are needed for BC to increase its convenience and comfort among users (Govindan, 2022).

- BC has a low throughput when it is compared to centralized databases, so high latency can be a problem for BC adoption. To illustrate, a key issue with an integrated ecosystem is that BC could not be as resilient as needed in terms of latency and data throughput. A high number of business transactions made by companies regarding CE practices may somewhat hinder BC performance. Therefore, low scalability and high latency may raise concerns about the feasibility of BC in the CE (Rejeb et al., 2022). It has to be noted that if a system is scalable, the latency should not go up as the transaction traffic on it increases.

-Businesses prefer private (permitted) blockchains over public ones due to privacy concerns and a reluctance to reveal sensitive information. However, this limits transparency and visibility's primary benefits and advantages. This is a significant challenge for BC to be used in CE practices. Establishing specific codes to protect legitimate CE activities and limit malicious members and potentially inappropriate behaviour may drive businesses to select public ones to benefit full advantages of BC (Rejeb et al., 2022).

- The ability to integrate different information systems, applications, and devices within and across the enterprise to access, share and share stakeholder data is called interoperability. Interoperability issues are mainly related to the incompatibility between existing (older) and new systems. The value of BC could be limited, and its adoption could be hampered if the systems of various CE stakeholders are not aligned. BC's full benefits can only be realized when the platforms used by businesses are interoperable. Increased interoperability reduces the time between circular economy processes, speeds up ordering, transferring, and paying, and ensures that products move on time efficiently (Rejeb et al., 2022).

-The complexity of BC is another challenge for adoption in the CE. It may be difficult to grasp new technology, and many problems would be faced while using BC can be prevented by continuing to use traditional information systems and databases (Wang et al., 2019). Many people are also unaware of its complexities and implications (Hunhevicz & Hall, 2020). This also makes it challenging for the whole supply chain to embrace the technology since it introduces numerous new concepts, such as public key, private key, and cryptography (Huang et al., 2022). Moreover, implementing blockchains may overcomplicate the current supply chain architecture (e.g., process delay and ease of use problems) (Rejeb et al., 2022). Therefore, adopting BC may be in second place for the CI partners regarding CE adoption.

4.2.8 Legal and Contractual Uncertainty Regarding Circular Economy and Blockchain

Various factors influencing the implementation of the CE in the CI regarding contractual topics are mentioned below.

-Early selection of contractors and manufacturers through planning, design and construction stages regarding CE requirements. Contract modifications to incorporate the CE perspective. Changes in the tendering and procurement phases per CE perspective (Charef & Lu, 2021).

-Choosing IPD (Integrated Project Delivery) and other project delivery methods paving the way for a collaborative work environment. Integrating CE into contractual requirements and assigning CE consultants to help with the design (Cruz Rios et al., 2021).

-Cost sharing among stakeholders to reduce the individual cost of maintaining the CE repository (Shojaei et al., 2021).

-Circular Product Design: slowing resource loop, enforcing sustainable procurement aligned with the CE (Khan et al., 2022; Cruz Rios et al., 2021). Smart contracts can be used in sustainable construction material procurement processes. The smart contracts can be coded in such a way that the payments of procured products can be executed if the products satisfy the sustainability prerequisites determined in the smart contracts automatically.

-The enhanced quality of life ideas through sustainability increases clients' motivation for a circular building from the initiation of the design process. (Kanters, 2020 and Böhmecke-Schwafert et al., 2022). Therefore, clients may change their preferences in favour of contractors specialized in CE topics in construction.

As seen in the above-pointed enablers, CE adoption requires changes in the way of working and causes some shifts in the roles and responsibilities of CI partners. Connectedly these changes cause contractual uncertainties regarding CE adoption.

Similarly, when BC technology is integrated as a catalyst on CE, it brings some changes as well. As a disadvantage, BC adoption has a disrupting effect on existing contractual conditions. Moreover, BC impacts the CI participants’ way of working, due to smart contracts. The smart contracts which emerged with BC adoption would automate contractual responsibilities and, increase the trust between CI participants.

However, a lack of regulatory or institutional support for the effective enforcement of contracts is a challenge to the successful application of BC. There are legal insufficiencies regarding the use of smart contracts as well. Therefore, mandated, clear and, complete directions are needed (Kouhizadeh et al., 2020).

In addition, since BC is a new technology, it is not well known, and there are few BC and smart contract developers. Therefore, BC technology must be supported by predefined standards, regulations, and effective governance structures to prevent conflicts and clarify actions.

4.2.9 BIM and Blockchain Integration Challenges

BIM represents digital innovation in the construction industry since BIM is at the heart of data management, information sharing, and collaboration. By integrating BIM and BC-based intelligent contracts (iContracts), it is possible to eliminate the trust problem in data transactions. An iContract would rely on and generate a lot of data transactions, and BC is a possible solution to eliminate the trust problem related to that data (McNamara & Scpasgozar, 2020). BIM Level 1 and Level 2 have a centralized structure and are prone to cause the formation of data silos, while BIM Level 3 is more collaborative but still works on centralized databases (Teisserenc & Sepasgozar, 2021). Therefore, BC-based icontracts can successfully combine contractual information with BIM Level 3 (McNamara & Scpasgozar, 2020). In addition, the security and transparency of the information produced through digital BIM models can be increased by BC integration. Hence, with the integration of BC, the credibility of construction projects and the collaborative work condition provided by BIM can be improved (Figueiredo et al., 2022). From the CE perspective, ensuring data accessibility and availability regarding assets and materials is important for the successful execution of CE (Charef & Lu, 2021). Therefore, using BC to enhance the security and traceability of data created in the BIM environment is critical for adopting the CE in the CI.

Despite the mentioned advantages of using BC, some challenging topics also exist.

-Unclear roles and responsibilities / Lack of enforceability is a fundamental obstacle since it is difficult to determine who is accountable (Teisserenc & Sepasgozar, 2021). To illustrate, who owns the model; who has the right to make modifications; who has the right to distribute; who will be accountable for any alterations or problems; how to protect copyright and, digital intellectual property; difficulties in risk and reward allocation (Turk & Klinc, 2017).

-A high computational power is needed to add the data generated in the BIM environment on the BC (Figueiredo et al., 2022).

-The data value chain in the CI is fragmented in data silos and this situation limits collaboration and data sharing. To illustrate, the data produced in the BIM model is currently kept in data silos containing different models and versions. In addition, BC technology has some issues regarding storage and scalability to run the BIM model entirely on the BC environment as a decentralized application (Teisserenc & Sepasgozar, 2021).

4.2.10 Operational and Supply Chain Risks

The CE concept and BIM application in the CI require cross-organizational collaboration and coordination among sector participants. BC technology paves the way for collaboration regarding data context. However, human-related topics, establishing cross-organizational collaboration and coordination, are challenges for adoption (Erol et al., 2022). In addition, the mentioned organizational collaboration and coordination may not be achieved when it is handled from a global perspective. There are several reasons for it, such as poor information technology systems, information sensitivity, poor planning of activities, poor supply chain management, supply chain inefficiencies (Teisserenc & Sepasgozar, 2021), and integration competition among supply chain partners (Bressanelli et al., 2018). Another item that confuses sector participants is an increased risk of codependency for different organizations or firms when adopting BC in the CE environment (Upadhyay et al., 2021).

Moreover, uncertainties regarding quantity, mix, quality, time, and place of the products which are at their end-of-use and quality degradation fear regarding the CI are important challenges for the adoption of the CE (Bressanelli et al., 2019 and Dulia et al., 2021). To illustrate, the uncertainties in mentioned fields decrease the economic profitability and cause problems in the capacity planning of companies. As a note, illegal disposals diminish the number of collected materials for recovery and form a challenge for CE application (Bressanelli et al., 2019).

Finally, the current building stock was not designed considering the CE and deconstruction perspective. Connectedly, applying CE principles under this condition requires much more time and an intensive labor force for the applicant company. This will increase the cost of the activity and lead to delays in the previously planned work schedule (Elghaish et al., 2022). Therefore, the adoption of CE principles will be hampered.

4.2.11 Inertia in Business to Change

A suitable environment and openness to change are needed for a possible transition to BC and CE-adopted CI. However, the CI is closed to any change in the way of working. In other words, any change in the industry diffuses very slowly, and the industry has an inertia to change.

Since BC has a decentralized structure, for the transition to a BC-supported CE, the companies should change their organizations from a centralized one to a decentralized one (Böhmecke-Schwafert et al., 2022). Additionally, they should review their business model from linear to circular and revisit their way of production or servicing (Rejeb et al., 2022). All these required changes mean a shift in corporate culture, which is not an easy decision and may hamper the transition idea. Unfortunately, all these mentioned changes and being open to changes have a cost for firms, workers, and supply chain partners of the companies (Upadhyay et al., 2021).

Moreover, a change in the business processes is required to be executed before the new technology implementation (Santana & Ribeiro, 2022). To be tried the new system, the business process should be prepared. Connectedly, the lack of organizational policies to adopt BC technology (Santana & Ribeiro, 2022) causes some challenges in preparing the business process before adopting a BC-enabled CE.

Disruptive technologies like BC require a preparation process for the desired change in the way of working. Despite the mentioned challenges and inertia in the business, adopting disruptive technologies like BC is also an opportunity and an enabler for development. During the BC adoption process, firms can create an innovative business model which increases operational efficiencies (Rejeb et al., 2022 and Kanters, 2020).

4.2.12 Financial Resources and Cost-Related Issues

As mentioned in the previous section, digital technology adoption cannot be thought of without operating, adoption, investment, and increased energy costs for all sectors (Feng et al., 2022), including the CI. Adopting the CE may cause a time mismatch between revenues and costs (Bressanelli et al., 2019). Since being a new market, revenue uncertainties, high investment costs, and lack of appropriate business models hinder the adoption of the BC-supported CE. Although the CE proposes to develop economic values thanks to eliminating waste and saving resources, due to the mismatch between income and expense (Bressanelli et al., 2019), and revenue uncertainty, there is little evidence of financial benefits in the short period. This situation is an important challenge for the adoption of the BC-enabled CE perspective (Kouhizadeh et al., 2020).

Considering the issues mentioned above, any sector participant, including the CI, will feel unwilling to take the initiative and make investments in new, high-cost, and unproven technologies. The mentioned unwillingness causes a scarcity of successful commercial applications (Böhmecke-Schwafert et al., 2022). Connectedly, the scarcity of successful business models and real-life examples will reduce the knowledge of sector participants on costs and resources to implement (Govindan, 2022).

As a final note, the higher price difference between virgin and recycled products is a major challenge for adoption (Dulia et al., 2021). In addition, due to uncertain demand for recovered products and insufficient market demand, the secondary materials market does not support the CE perspective (Erol et al., 2022).

4.2.13 Lack of Awareness-Related Challenges

Lack of shared goals, such as a strategic orientation (Dwivedi & Paul, 2022) and a corporate strategy (Mojumder & Singh, 2021) related to overcoming green issues among different partners, is a challenge for CE adoption. Connectedly, the BC concept also requires in-detail investigations in other fields (Kouhizadeh et al., 2020), including integrating BC with the CE. This is because the adoption of BC is not tested in different CE activities (Rejeb et al., 2022). The integration of BC and CE has some points that require clarification. Hence this situation possibly affects the adoption practices of risk-averse CI participants.

Several organizational barriers prevent organizations from adopting BC technologies, including existing organizational policies and culture, lack of knowledge and appropriate management behaviours, and a lack of collaboration and coordination (AlShamsi et al., 2022). The lack of management is important since the managers execute the adoption decision. Implementing BC in the CE requires knowledge and managerial support (Rejeb et al., 2022). The lack of management shows itself as management unwillingness (Khan et al., 2022), immature management practices (Dwivedi & Paul, 2022), unavailability of top management (Rejeb et al., 2022), and slow decision-making and implementation processes

(Böhmecke-Schwafert et al., 2022). All these managerial issues negatively impact the implementation process of a BC-supported CE. The existence of mentioned managerial arguments is not deniable in the CI regarding the adoption of the BC-supported CE.

At that point, the importance of enterprise knowledge training (e.g., educating designers, building owners, supply chain partners, and engineers) comes forward for the implementation of BC in the CE (Khan et al., 2022). Employee commitment and management commitment will be increased, and the failure of the adoption process will be diminished (Rejeb et al., 2022) with the education since they would have a background regarding the CE and BC concepts. Mainly, manager education regarding the CE and BC yields more beneficial results since a better knowledge management and decision-making procedure would be achieved. Therefore, top management commitment to the adoption of CE and BC can also be accepted as an enabler since it leads to better knowledge management and improved decision-making (Rejeb et al., 2022).

4.2.14 Lack of Organizational and Business Model Readiness

Centralized organizational structures such as centralized databases, digital twin solutions, IoT management (Teisserenc & Sepasgozar, 2021), and a strong industrial concentration on linear business models (Bressanelli et al., 2019) are the prominent challenges to the adoption of a BC-enabled CE for the CI. Almost all current micro and macro indicators like GDP and company turnover rate are based on a linear economy mindset, aiming to maximize throughput and sales. However, the CE requires moving from a volume-driven economic viewpoint toward a more holistic, economic, environmental, and social perspective (Bressanelli et al., 2019). The current position of the CI matches the aim of a purely linear focus. Therefore, changing this linear focus to a circular one forms a challenge for the CE adoption in the CI such as the profit versus sustainability paradox which also hinders the adoption of BC-based CE innovation (Böhmecke-Schwafert et al., 2022).

In addition, BC and CE implementation requires organizational readiness (Shojaei et al., 2021). To illustrate, developing BC and CE innovation requires the willingness for sustainable development and the motivation to transform each company branch, including financial and human resources, to implement relevant applications (Böhmecke-Schwafert et al., 2022). A division for demountable modules and storage should be hired. A new budget division may be required. New roles will be created, and skilled persons will be needed regarding the CE and recovered materials. New and reclaimed materials databases should be prepared. Forming and managing collaborative platforms is a need (Charef & Lu, 2021).

Connectedly, BC and CE implementation require intra and inter-organizational relationships (Shojaei et al., 2021). This requirement may cause the paradox of simultaneous competition and cooperation between different organizations. Even though profits are higher when firms move together, sharing marketing strategies, or private subjects, design skills are the main issues. (Upadhyay et al., 2021).

Besides all of these, BC technology utilization in the building sector is still a new concept and, in its infancy, (Shojaei et al., 2021). Connectedly, it is hard to adopt BC for the entire supply chain because of the lack of knowledge about its intricacies and ramifications. Therefore, uncertainty exists regarding whether BC truly fits CE requirements. Additionally, there is no clear answer to the question, "Is BC really necessary?" (Böhmecke-Schwafert et al., 2022).

As a final note, the challenge which organizations face is keeping up with the evolution of technology; in other words, tracking the continuous development of new technologies and upgrading them is very difficult (Khan et al., 2022).

4.2.15 Regulations-Related Challenges

Since it is a new topic, there are no settled regulations for implementing the technology (Rejeb et al., 2022). Therefore, for the successful adoption of a BC-based CE, there is a need for new regulations, including contemporary topics such as digitalization, reuse and repair, and decentralized business models. Uncertain, insufficient regulations and compliance (Erol et al., 2022) hinder the adoption of BC in the CE. To illustrate, smart contract technology is the core of BC and, integrating BC into the CE requires smart contracts inevitably. However, as part of a BC ecosystem, smart contracts are constructed on rules defined by software engineers and coders. They determine the applications, architecture, and design of the network. The result may cause several compliance problems in the industry and compliance with regulations (Rejeb et al., 2022). Connectedly, when regulations or institutions support the effective enforcement of contracts through exchanging goods and capital, smart contracts will become popular among CE practices. To explain the actions of the participants and prevent conflict, BC utilization at the inter-firm level requires predefined codes, standards, and governance structures (Kouhizadeh et al., 2020).

Considering the uncertainties mentioned above and insufficiencies and lack of clear incentives/governmental support, it is seen that the current regulations lack to persuade construction societies over the world regarding CE and BC adoption (Elghaish et al., 2022).

Currently, regulations and codes impede the reuse and repair of building components. There is a lack of information regarding salvaged materials' availability, quality, and quantity (Elghaish et al., 2022). When the regulation topic is thought within the CI, adding CE in building codes (executing a compulsory plan for building disassembly), reaching a consensus to use the CE concept, and preparing clear guidelines about different CE strategies can help in the adoption (Rejeb et al., 2022).

4.2.16 Policy Decision-Makers and Government Related Challenges

Lack of proper vision in terms of goals, objectives, targets, and indicators for the circular supply chain (Dulia et al., 2021) is a challenge for the adoption of the CE. The lack of proper vision is caused by political decision-makers' lower level of know-how in the CE (Erol et al., 2022). The lack of adequate vision and CE experience of policy decision-makers results in a lack of policymaker support and clear incentives (e.g., funding and relevant regulations) for BC-based CE adoption (Böhmecke-Schwafert et al., 2022). The policy maker support includes education of workers regarding BC and CE, increased obligation regarding sustainability and transparency topics, a sufficient amount of funding and relevant regulations (Böhmecke-Schwafert et al., 2022), encouraging people to change their purchasing habits towards more environmentally friendly products (Erol et al., 2022). The mentioned barriers negatively affect the CI's transition toward BC and CE. Educating CI participants, obligating sector participants to use sustainable products starting from design, and funding the CI regarding CE-friendly activities can advance the adoption of the CE.

Finally, existing policies, taxation systems, and incentives do not align with the CE paradigm (Bressanelli et al., 2019). In particular, taxation policies have an important role in adopting the CE in the CI. To illustrate, increasing demolition and carbon taxes, landfill fees, raising taxes on new construction activities and reducing levies for adaptive building, and retrofitting existing structures instead of demolition can accelerate the adoption of the CE process. In addition, increasing levies on virgin materials, allocating public funding to circular design and construction, and incentivization to use prefabrication and modular design can also speed up the transition process.

4.2.17 Lack of Supply Chain Support

Lack of supply chain support is a challenge for CE adoption. This challenge exists because of the limited number of CE-adopted companies (Bressanelli et al., 2019). In other words, if one company wants to change its business model to a circular one, it will face difficulties in finding partner firms to make circular product trade, for example. Due to this problem, the firm selected circularity may lose its market share (Böhmecke-Schwafer et al., 2022). It is called the sustainability versus product paradox. Sustainability is not an indicator of success. Therefore, there is risk-averse behaviour. This situation is valid for construction companies as well.

4.2.18 Sustainability vs Profit Paradox

In the CE, volume-based economics must be pushed aside in favour of a more holistic approach that encompasses economic, environmental, and social concerns. Therefore, BC-enabled CE innovation is hindered by tensions between profit and sustainability objectives (Bressanelli et al., 2019).

In addition, the CE aims to extend the usable life period of the materials and products as a design requirement to last practices. Based on these practices, predictive maintenance studies needed to be completed (Bressanelli et al., 2019). Based on the data recorded on BC, these predictive maintenance processes can be completed successfully, without any data loss. However, the mentioned predictive maintenance studies cause a lower product circulation ratio than in the linear economy, called market cannibalization (Bressanelli et al., 2019). This situation decreases the profit of product suppliers, hence forming a challenge for the transition to the CE.

4.2.19 Changing Settled Habits and Ideas

The CI inherently accepts and applies changes slowly. Therefore, changing cultural habits in the CI and changing people's mindsets is a hurdle (Wang et al., 2019). The recycling and reusing of building materials are narrowed down to particular facilities since the CE concept is not widely used in the CI. Moreover, these efforts are also narrowed down to specific branches, such as steel structures or masonry materials (Shojaei et al., 2021). Connectedly, difficulties in changing the linear mindset, in other words, linear lock-in (primarily due to insufficient awareness and commitment of top management and workers) is a challenge for adopting the CE (Bressanelli et al., 2019) in the CI. Due to the difficulties in changing settled habits in the CI, there is a lack of community support and customer readiness regarding the shift to a BC-based CE.

4.2.20 Challenges Due to CI Characteristics

The structural fragmentation of the industry and lack of industry-specific procedures cause challenges (Dwivedi & Paul, 2022 and Teisserenc & Sepasgozar, 2021) in the CE and BC adoption process in CI. The main sign of being a fragmented industry is the excessive number of competitive companies and professions running in that industry. This sign matches the CI properties. Any construction project has multiple processes and requires the involvement of multiple competing organizations and professions having conflicting interests to be completed (Nawi et al., 2014).

Connectedly, this competition is the main challenge for the trust in CI-related data sharing and governance and, therefore, collaboration, coordination, and improvement culture in the industry. On the contrary, the adoption of blockchain requires an improved data-sharing mechanism in its origin and enhanced collaboration and coordination. Therefore, BC-enabled CE adoption in CI may face the mentioned challenges.

In addition, incorporating building materials in CE is a labor-intensive process (Shojaei et al., 2020) starting from the demolition stage. Moreover, when all the products have to be sent back to the producers or specialized firms for refurbishing or remanufacturing, CE will significantly increase transportation costs (Bressanelli et al., 2019).

Next, item-level tracking is a need for the successful adoption of CE to calculate the real effect of CI activities on the environment. Although using BC in item-level tracking can be beneficial for the ease of CE adoption, when product diversity is taken into account, the difficulty and cost of implementing such a system for a construction project become an important challenge (Santana & Ribeiro, 2022). The mentioned difficulty is due to a lack of information about a product's lifecycle

(Santana & Ribeiro, 2022), the loss of user control over the product (Bressanelli et al., 2019), and incomplete/broken information flow across phases of the product lifecycle (Teisserenc & Sepasgozar, 2021). There is an interruption problem with the information flow due to the long service life of buildings, their components, and the existence of multiple professions like; design, construction, operation, maintenance, and renovation throughout the life cycle of structures (Shojaei et al., 2021).

The design for the deconstruction principle is an important topic in the adoption of CE in CI. Most of the existing buildings were not designed for deconstruction. Therefore, there is darkness regarding the provenance of materials used in the existing buildings. Moreover, even though the design of the building was performed suitable for deconstruction, there is no absolute rule that products collected from an existing building will be reused (Shojaei et al., 2020).

Finally, it isn't easy to standardize and transport salvaged building components. Similarly, since salvaged building components are not well documented in terms of their availability, quality, and quantity, value estimation of salvaged building materials is a challenging topic. Reusing salvaged materials in the new designs is disregarded by designers due to quality deterioration. Connectedly, these mentioned challenges form barriers to the adoption of CE adoption in CI. Especially, lack of documentation and data hinders BC adoption in CI (Elghaish et al., 2022 and Bressanelli et al., 2019).

4.2.21 Environmental and Ecological Perspective

Despite its ability to leverage sustainability practices, BC technology also has a sustainability tension as its operation is very energy-intensive, leading to considerable environmental impact (Kouhizadeh et al., 2020). In other words, the CE's goals of benefiting the environment, reducing energy consumption, and promoting renewable energy are in opposition to blockchain's significant electricity consumption (Rejeb et al., 2022). In addition, the following topics are also mentioned in the literature as barriers to CE adoption.

- Limited use of biodegradable materials in circular supplies is a challenge to the success of CE (Dulia et al., 2021).
- Product recovery lacks validity in terms of environmental benefits (Erol et al., 2022).
- There may be some inefficiencies regarding the eco-efficiency of technological and renovation processes (mostly in recycling) (Bressanelli et al., 2019).
- Recycling and reusing construction materials are restricted to isolated activities of specific establishments (Shojaei et al., 2020).

4.3 The Survey

This section demonstrates the demographics of participants and the survey results, respectively. In total, 29 professionals participated in the survey. While 20 participants completed the survey study, 9 answered the questionnaire partially, leaving out the last four questions. The survey form is presented in Appendix B.

4.3.1 Demographics of Participants

Figure 4.1 presents the professions of survey participants. Most participants are from the civil engineering and architecture fields, and four participants are from other disciplines.

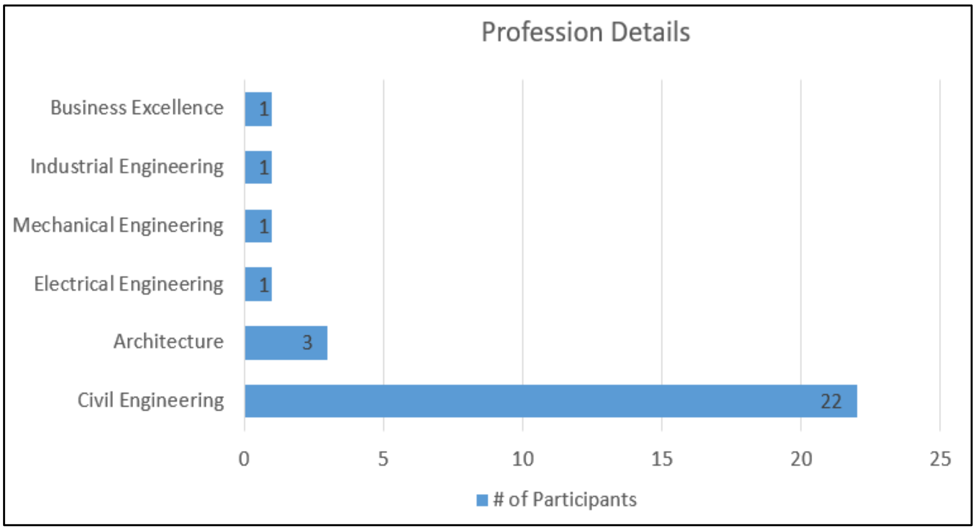

Figure 4.1. The participants' professions

Figure 4.2 shows that most of the participants work in design/engineering and consultancy companies and universities.

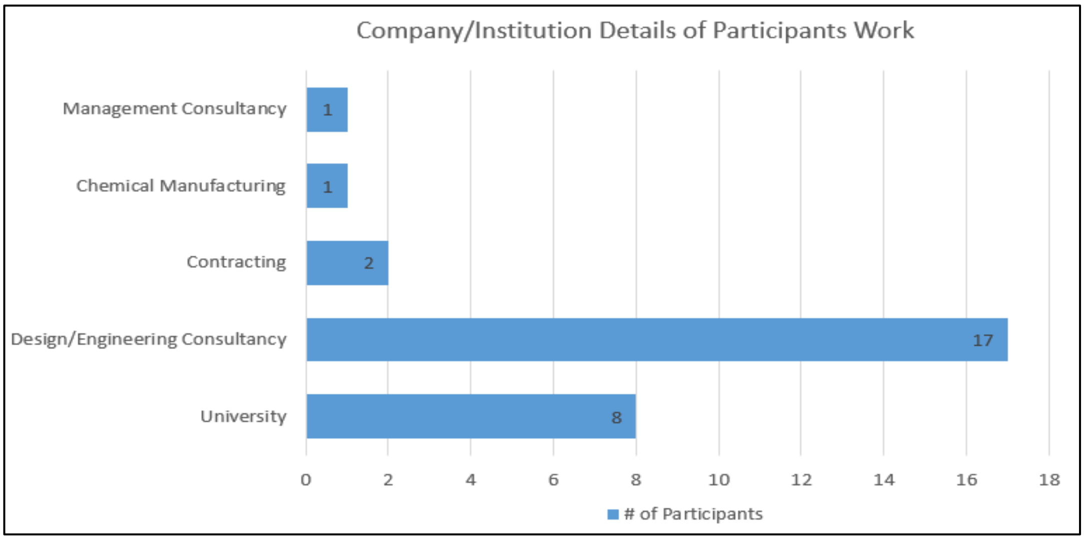

Figure 4.2. The company/institution details of the participants

Table 4.1 depicts the distribution of participants' departments, and Table 4.2 presents their experience levels. The majority of the participants have more than five years of experience.

Table 4.1. The departments of participants

Departments	# of Participants
Business Intelligence	1
Contract Management	1
Tendering	2
Planning	2
Design	12
Education and Research	8
Progress Payment	1
Management	1
Procurement	1

Table 4.2. Experience levels of participants

Experience Levels	# of Participants
Less than 5 years	4
5-10 years	9
10-15 years	1
15-20 years	3
20-30 years	9
More than 30 years	3

4.3.2 Survey Results and Discussions

4.3.2.1 CE and BC Knowledge Level

Figure 4.3 depicts the sector experience and BC and CE knowledge levels expressed by survey participants. The participant set includes four members stating that they do not know BC. On the other hand, each participant knows CE. While three members in the group expressed that they know BC very well (at level 5), any member expressed that they know BC very well (at level 5) for CE. Additionally, it is seen in Figure 4.3 that the sector experience does not have a direct relation to the CE and BC knowledge of participants. There are participants with more than 30 years of experience and no knowledge of BC. Additionally, there are members with less than five years of experience and a good level of BC and CE knowledge. Moreover, participants' average knowledge levels (0 to 5 scale) are 2.55 for CE and 1.93 for BC. Therefore, CE is better known than BC. This situation is parallel to the position in the literature.

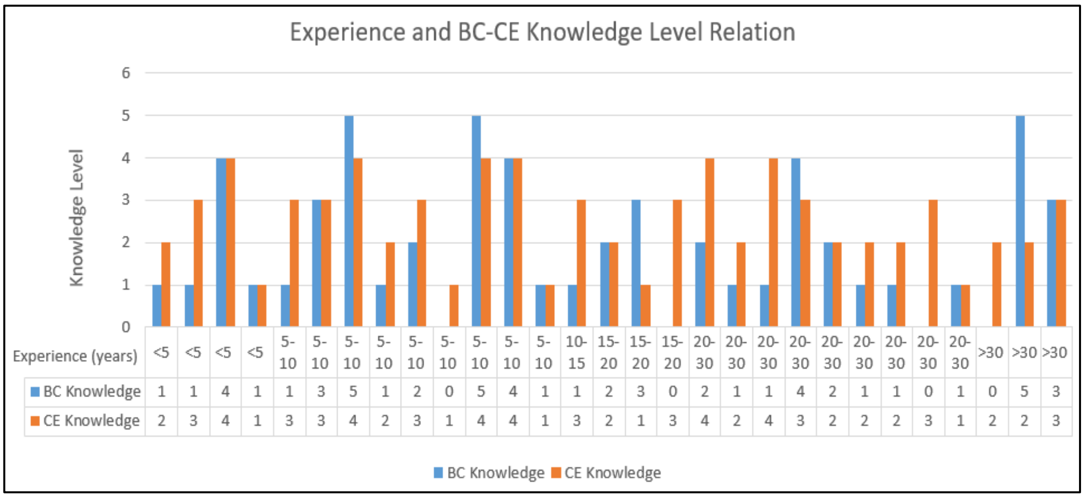

Figure 4.3. Shows the sector experience and BC-CE knowledge of each participant

Figure 4.4 shows participants' answers to the following question; "*At what level/how well do you think blockchain can support the circular economy?*" Participants' responses who stated that they have 0-level BC or CE knowledge are excluded from

Figure 4.4. While only two participants reflect a moderate (level 3) level, seven participants think that BC supports CE at low levels (levels 1 and 2). However, nine participants believe BC supports CE at a high level (level 4 and level 5). It is clear that the participants with a wide range of perspectives attended the conducted survey.

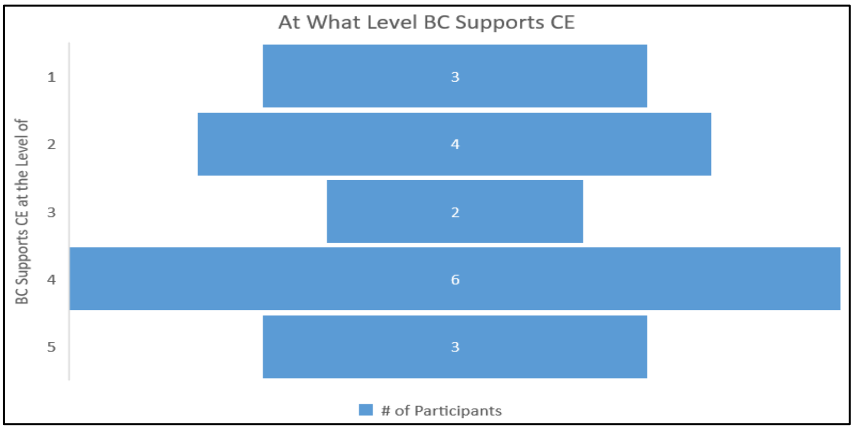

Figure 4.4. Shows at what level BC supports CE

In addition, the participants with (1-2)/5 levels of CE and BC knowledge expressed that BC supports CE at the rate of 2.14/5 on average. On the other hand, the participants with (3-4-5)/5 levels of CE and BC knowledge stated that BC supports CE at the rate of 3.5/5 on average. Hence, the survey results show that participants with higher CE and BC knowledge levels think BC supports CE at a higher level.

Apart from the topics mentioned above, five participants stated that they encountered CE or BC-oriented practice in their professional lives. The first one is a CE-related practice about retrofitting and repairing existing buildings instead of demolishing and reconstructing them. The second one is also about CE; it concerns using unnecessary residual rebars during construction instead of sending them to garbage. The third one points to academic studies. The fourth is R&D work related to developing products and solutions for circular construction methods regarding precast concrete buildings designed to disassemble and reuse structures. The final one is about research on blockchain and smart contract technologies.

Regarding these five answers, CE-related activities are executed more frequently in practice than BC-related activities. In addition, although the BC and CE concepts are used individually in the construction industry, they are not used together in practice. This finding is similar to the literature.

4.3.2.2 Enablers and Barriers

The following question was asked to the CI participants "*How would you express your perception regarding the effects of the following barriers and enablers on the successful usage of blockchain/circular economy concepts in the construction sector on a 1 to 5 Likert scale?*" to assess their views. Participants' responses who stated that they have 0-level BC or CE knowledge are excluded. The answers to the barriers are discussed in three topics which are technological barriers, organizational barriers, and environmental barriers. Additionally, the answers for the enablers are discussed in the enablers topic.

4.3.2.2.1 Technological Barriers

Survey participants' views regarding the effects of pre-determined 12 technological barriers are presented below in Table 4.3 and Figure 4.5. The complete list and definition of technological barriers can be found in Table 4.4.

Table 4.3. Number of participants per effectiveness of each technological barrier

		Technological Barriers											
		BT1	BT2	BT3	BT4	BT5	BT6	BT7	BT8	BT9	BT10	BT11	BT12
Effectiveness Level	N/A	1	1	0	1	0	0	2	1	1	0	1	1
	1	3	0	0	1	4	1	1	0	0	0	1	0
	2	1	3	1	4	2	1	3	2	2	3	1	2
	3	6	4	6	5	6	6	6	7	8	5	7	3
	4	8	11	8	6	6	9	9	8	6	9	9	8
	5	2	2	6	4	3	4	0	3	4	4	2	6

The data in Table 4.3 are depicted in Figure 4.5. Figure 4.5 shows that most participants think the technological barriers affect the successful usage of BC/CE concepts in the construction industry moderately (level 3) and highly (level 4). The very high effect level (level 5) is in third place after levels 3 and 4.

Table 4.4. The most common level of effect of technological barriers

Technological Barriers	Level of Effect on the successful usage of BC and CE in the CI
BT1- Responding capacity of BC and CE	Moderate/High
BT2- Problems inherent in the construction sector	Moderate/High
BT3- Existing infrastructure-related problems	Moderate/(Very)High
BT4- Blockchain limitations and requirements	Moderate/High
BT5- Data-related issues (false/incomplete information entry, some cracks in security, privacy, confidentiality)	Moderate/High
BT6- Determination of the appropriate level of transparency/resistance to a high level of transparency	Moderate/High
BT7- BC compatibility, availability, interoperability, scalability, and latency challenges	Moderate/High
BT8- Complexity of the blockchain (complexity of the technology to grasp)	Moderate/High
BT9- Ownership and liability issues (unclear roles, difficulties, and responsibilities in protecting intellectual property rights)	Moderate/High
BT10- Legal and contractual uncertainty regarding CE and BC	Moderate/High
BT11- BIM and blockchain integration challenges	Moderate/High
BT12- Blockchain is a new technology, so it is not well known, and there are few blockchain and smart contract developers	High/Very High

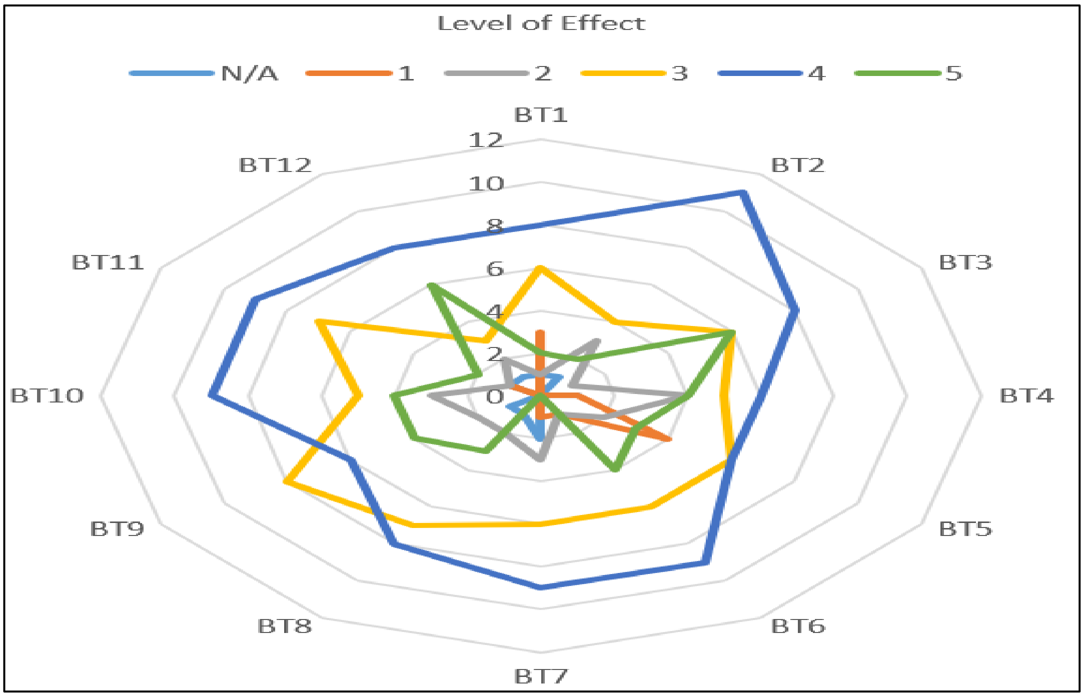

Figure 4.5. Number of participants per effectiveness of technological barriers

Table 4.4 presents the list representing the majority's ideas regarding the effect of each technological barrier on the successful usage of BC and CE in the CI. The barriers BT2, BT6, BT7, BT10, BT11, and BT12 are the prominent ones against the successful adoption of CE and BC in CI. BT12 (blockchain is new and not well known) is particularly significant because the majority states that BT12 affects the adoption and use at high and very high levels. Here, BT3 (existing infrastructure-related problems) has to be also explained. BT3 affects the adoption and use at high and very high levels, similar to BT12. However, an equal number of respondents consider BT3 to be both very highly and moderately effective.

It is mentioned in the literature that BC can not guarantee perfect security and privacy protection. On the contrary, some stated in the literature that the privacy and anonymity of transactions in the BC environment are secured. In short, there is confusion in the literature about whether using BC is secure. In addition to the literature, this survey study revealed the personal perceptions of CI participants regarding the effectiveness level of this possible security crack in BC. The cracks regarding security and privacy in BC have been seen as highly and moderately effective in the first place and lowly effective in the third place in the successful usage of BC and CE in CI. The sharp increase in the effect level 1 for BT5 (cracks in security, privacy, confidentiality) can be seen in Figure 4.5. To sum up, this situation shows participants' confusion regarding the effect level of cracks in security and privacy provided by BC in the successful usage of BC-supported CE in the CI.

4.3.2.2.2 Organizational Barriers

The views of survey participants regarding the effects of the pre-determined five organizational barriers are presented below in Table 4.5 and Figure 4.6.

Table 4.5. Number of participants per effectiveness of each organizational barrier

		Organizational Barriers				
		BO1	BO2	BO3	BO4	BO5
Effectiveness Level	N/A	1	1	0	0	0
	1	1	1	1	1	1
	2	3	2	2	2	2
	3	5	4	1	3	7
	4	9	8	6	8	7
	5	2	5	11	7	4

Both Table 4.5 and Figure 4.6 depict that most participants think the organizational barriers affect the successful usage of BC/CE concepts in the construction industry highly (level 4) or very highly (level 5). The moderate effect level (level 3) is in third place after levels 4 and 5. Compared to technological barriers, the weight of the moderate level of effect is decreased, and the weight of the high level of effect is increased. BO1 represents operational and supply chain risks (e.g., difficulty with establishing cross-organizational collaboration and coordination, risk of codependency for different organizations or firms due to the adoption of a BC-enabled CE). Most participants state that BO1 has a moderate/high effect on the successful usage of BC and CE in the CI.

BO2 represents financial resources-related issues (e.g., high purchasing, implementation, material costs, (upfront) investment of circular economy/blockchain, and in return, uncertain revenues). The majority of participants state BO2 has a high/very high effect on the successful usage of BC and CE in the CI.

BO3 represents the lack of awareness (unavailability of management commitment, absence of corporate strategy). The majority of participants reveal BO3 has a high/very high effect on the successful usage of BC and CE in the CI. Similarly, the awareness level was mentioned as an important and unexplored factor in the literature. Connectedly, the aim of this thesis study is about determining the awareness levels of CI participants regarding the adoption of CE and BC concepts in CI. Therefore, the importance placed on the lack of awareness level (BO3) by survey participants shows this thesis study's necessity. In that sense, the results are parallel to the literature.

BO4 represents the inertia in business to change (e.g., the absence of organizational policies to adopt blockchain and circular economy). Most participants state that BO4 has a high/very high effect on the successful usage of BC and CE in the CI.

BO5 represents organizational and business model readiness (infancy of current models on blockchain and circular economy, lack of knowledge on intricacies and ramifications). The majority of participants find BO1 as moderately and highly important regarding the successful usage of BC and CE in the CI.

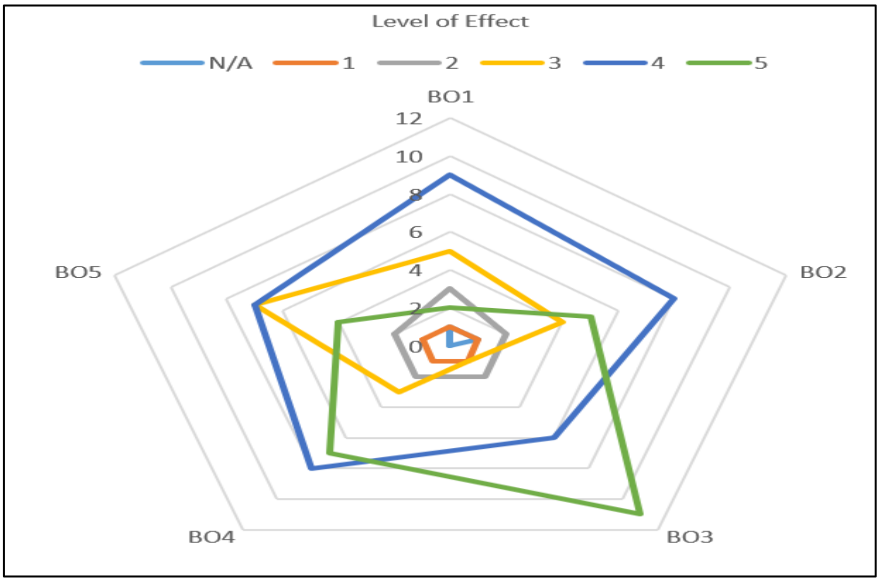

Figure 4.6. Number of participants per effectiveness of organizational barriers

4.3.2.2.3 Environmental Barriers

The views of survey participants regarding the effects of pre-determined 13 environmental barriers are presented below in Table 4.6 and Figure 4.7.

Table 4.6. Number of participants per effectiveness of each environmental barrier

		Environmental Barriers												
		BE1	BE2	BE3	BE4	BE5	BE6	BE7	BE8	BE9	BE10	BE11	BE12	BE13
Effectiveness Level	N/A	0	0	1	1	1	0	0	0	0	0	1	2	0
	1	0	0	0	1	0	0	1	0	0	0	0	3	1
	2	0	2	1	2	0	1	2	2	2	1	1	5	1
	3	6	1	4	5	2	3	3	7	8	7	2	3	5
	4	6	7	9	6	13	11	9	7	5	7	12	5	8
	5	8	10	5	5	4	5	5	4	5	5	4	2	5

Table 4.6 and Figure 4.7 depict that the majority of the participants think the environmental barriers affect the successful usage of blockchain/circular economy concepts in the construction industry moderately (level 3), highly (level 4), or very

highly (level 5). The moderate effect level (level 3) is in third place after levels 4 and 5.

Table 4.7. The most common level of effect of environmental barriers

Environmental Barriers	Level of Effect on the successful usage of BC and CE in the CI
BE1- Uncertain and insufficient regulations/need for new regulations, including contemporary topics such as digitalization, reuse and repair, and decentralized business models	High/Very High
BE2- Lack of governmental incentives.	High/Very High
BE3- Lack of supply chain support regarding the CE and BC integration	High/Very High
BE4- The sustainability vs. profit paradox (market barrier, and sustainability are not the success indicators)	Moderate/High
BE5- Lack of awareness, understanding, know-how, and proper vision of policy decision-makers regarding BC and CE	High/Very High
BE6- Changing settled habits, ideas/cultures (resistance to changing traditional processes)	High/Very High
BE7- Lack of community support and customer readiness for circular economy and blockchain	High/Very High
BE8- CI characteristics (e.g., lack of industry-specific procedures, structural fragmentation of the industry)	Moderate/High
BE9 represents the complexity of the recycling process and inefficient design routes for recovery products	Moderate/High/Very High
BE10- Lack of information regarding provenance, unfinished parts of materials/tracking difficulties of materials through their lifecycle.	Moderate/High

Table 4.8. The most common level of effect of environmental barriers (Continued)

Environmental Barriers	Level of Effect on the successful usage of BC and CE in the CI
BE11 represents the lack of awareness and uncertainty in life cycle thinking (uncertainties at the products' end of life and quality assurance throughout the life cycle of a product)	High/Very High
BE12 represents the environmental and ecological burden of the blockchain (Energy consumption of blockchain, high energy costs)	High/Low
BE13-Standards and compliance issues (lack of standardization, legal disputes and compliance issues regarding blockchain and circular economy, illegal use of blockchain).	Moderate/High/Very High

According to the participants, compared to BE1, BE2 is a more challenging barrier. BE4 is not seen as important as the previous ones. For BE9, the moderate effect level option takes the first place, but the high and very high effect levels have the same number of supporters behind the moderate effect. BE12 is seen as the least effective barrier. In other words, according to CI participants, it is possible for this barrier to have a low effect on the successful usage of BC and CE in the CI.

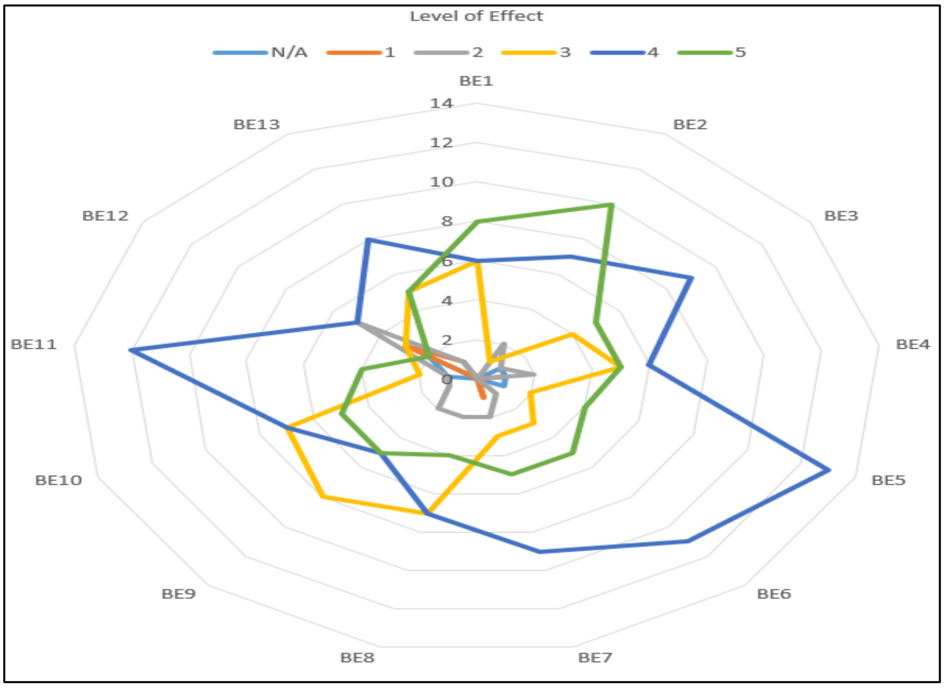

Figure 4.7. Number of participants per effectiveness of environmental barriers

4.3.2.2.4 Co-evaluation of Technological-Organizational-Environmental Barriers

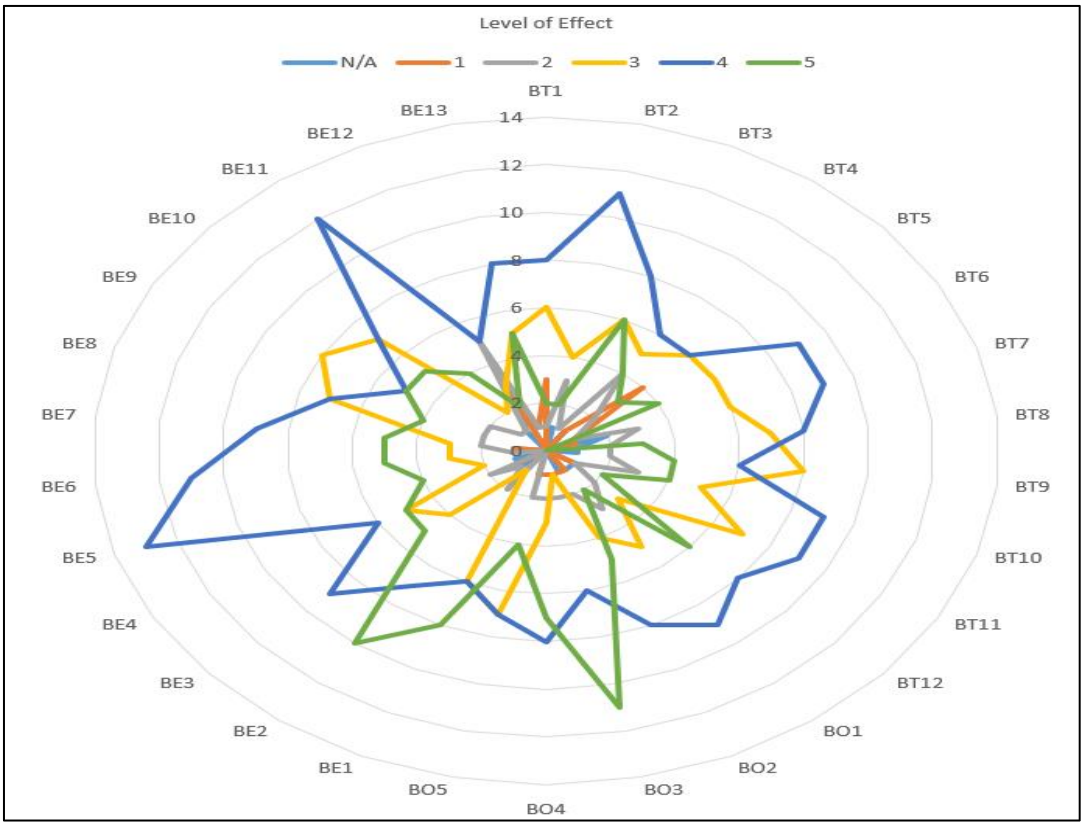

Figure 4.8. Number of participants per effectiveness of all mentioned-TOE barriers

The dominant position of the high effect level (level 4) is seen when all the barriers are collected together. The moderate and very high-level effects seem to be equal in the general view, but the high-level effect has two spikes for BO3 and BE2, which the moderate effect does not have.

Based on the view in Figure 4.8, the prominent barriers can be listed as a first set as follows;

- BE5: Lack of awareness, understanding, know-how, and proper vision of policy decision-makers regarding blockchain and circular economy

- BE11: Lack of awareness and uncertainty in life cycle thinking (uncertainties at the products end of life and quality assurance throughout the life cycle of a product)
- BO3: Lack of awareness (unavailability of management commitment, absence of corporate strategy)
- BT2: Problems inherent in the CI
- BE6: Changing settled habits, ideas/cultures (resistance to changing traditional processes)

As a second set, the following barriers can be listed;

- BO1: Operational and supply chain risks (e.g., difficulty with establishing cross-organizational collaboration and coordination, risk of codependency for different organizations or firms due to adoption of BC-enabled CE)
- BE3: Lack of supply chain support regarding the circular economy and blockchain integration (the presence of an informal system is a challenge for the circular economy and blockchain technology's successful usage)
- BE7: Lack of community support and customer readiness for circular economy and blockchain
- BT6: Lack of transparency and traceability in the (construction) supply chain, determination of the appropriate level of transparency/resistance to a high level of transparency
- BT7: Blockchain compatibility, availability, interoperability, scalability, and latency challenges (lack of tools and apps for blockchain integration)
- BT10: Legal and contractual uncertainty regarding circular economy and blockchain
- BT11: BIM and blockchain integration challenges (e.g., difficulty in tracking changes in BIM, lack of storage and scalability)
- BT12: Blockchain is a new technology, so it is not well known, and there are few blockchain and smart contract developers

4.3.2.2.5 Enablers

The following question, "*How would you express your perception regarding the effects of the following enablers on the successful usage of blockchain/circular economy concepts in the construction sector?*" was asked to the participants to understand their perspectives regarding the effect levels of provided enablers. The mentioned enablers list in the question can be seen in Appendix B, question 12. In response, the following enablers are accepted as moderately, highly, or very highly effective in the adoption and successful usage of BC and CE in CI.

- Advances in big data and data analytics enhance the usability of BC. Connectedly, designing databases regarding reusable components for the CI helps to adopt CE and BC in CI. (Highly effective)
- Ability to use process digitalization, digital and 3D printing, the internet of things (IoT), automation, robotics, and Industry 4.0 technologies in the construction domain. (Highly effective)
- Integrating circular economy in contractual requirements and assigning circular economy consultants to help with design (Highly effective)
- Increased incentivization, creating tax deductions for circular design strategies, raising taxes on virgin materials, allocating public funding to circular design and construction, increasing taxes on new construction, and reducing taxes for the adaptive building. (Very highly effective)
- Client's motivation for a circular building from the beginning of the design process (Highly/Very highly effective)
- Improved quality of life through increased sustainability thanks to blockchain-enabled circular economy (Moderately effective)

In addition, Figure 4.9 shows participants' responses to the following question; "*Do the enablers address the challenges for transitioning into a blockchain-supported circular economy? At what level*? " The answers of participants who stated that they have 0-level BC or CE knowledge are excluded from Figure 4.9. In Figure 4.9, it is seen that nobody selected level 5; however, the majority of participants selected level

3 and level 4. Therefore, it can be stated that although the enablers do not address barriers completely (at level 5), they may provide partial solutions to the transition into a blockchain-supported circular economy in CI.

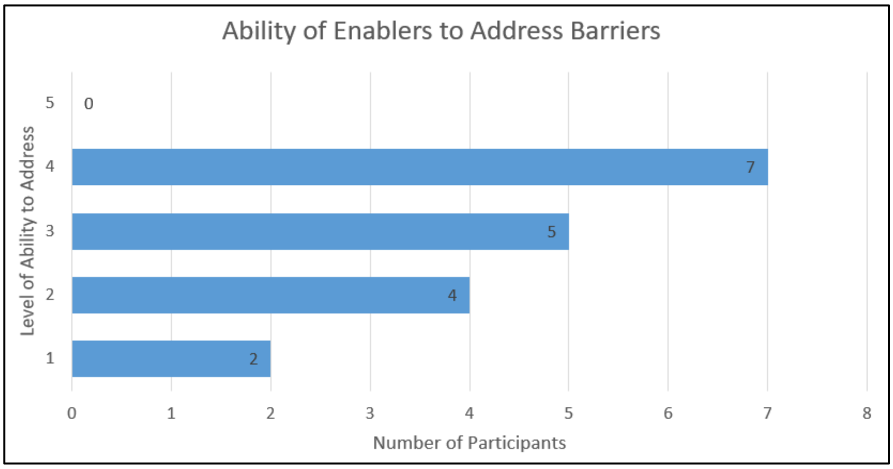

Figure 4.9. The ability of enablers to address the barriers

In addition, the participants with (1-2)/5 levels of CE and BC knowledge expressed that enablers address barriers at the rate of 2.29/5 on average. On the other hand, the participants with (3-4-5)/5 levels of CE and BC knowledge stated that enablers address barriers at the rate of 3.17/5 on average. Hence, the survey results demonstrate that participants with higher CE and BC knowledge levels think enablers address barriers at a higher level.

Moreover, there is a strong relationship between barriers and enablers. Any barrier has the potential to be converted into an enabler. For example, the lack of education is a barrier to the adoption and implementation of BC and CE in CI. Therefore, activities related to educating people can be seen as enablers. Based on this point of view, the suggestions of survey participants were asked in terms of removing the barriers to BC and CE adoption and usage in the construction industry. The answers are discussed in this and the following paragraphs. Enhancing the knowledge levels of participants and making the stakeholders aware of the benefits of using these technologies were suggested to remove barriers. If the knowledge levels increase, the benefits and disadvantages of adoption decisions regarding CE and BC will be made more consciously and easily. Additionally, the importance of government incentives was stressed by participants. If the government provides the needed incentives, the initial investment and implementation costs may be diminished, and sector stakeholders find it profitable to adopt BC and CE in their works.

Another participant suggests organizing workshops with the participation of all sector contributors, including material producers, designers, contractors, logistic firms, and users of CI outputs. The main objective of this workshop would be to discuss how to apply BC and CE and their necessities in the CI. Within these workshops, the demands and wishes of sector participants should be determined. Next, a program with a realistic schedule should be prepared by an organization that is in contact with governmental authorities to prepare and improve regulations regarding BC and CE usage in CI. Moreover, adding the CE and BC concepts to the standards and codes is suggested as an enabler for the adoption of these concepts in CI. Additionally, two participants see educating people and new regulations as the main enablers. As mentioned in the literature for other industries, these enablers are valid for CI as well. Educating people, especially top managers, regarding BC and CE topics would increase the accuracy of decisions made by them and increase the tendency to adopt these technologies since the decision-making authority belongs to them.

Finally, and as mentioned in the literature, changing settled habits is a major hurdle to adopting new technologies. Connectedly, one participant states that CI comes behind all technological enhancements and sees the comfort zone of people and companies and their settled habits as the main reason for this situation. Therefore, the participant suggests disturbing this comfort zone as an enabler for the adoption of CE and CE in CI.

Perceptions of participants regarding the effects of enablers on barriers were asked, and the answers are presented in Figure 4.10, and prominent answers are explained as follows. The question and the barrier and enabler information and explanations can be seen in Appendix B, question 13.

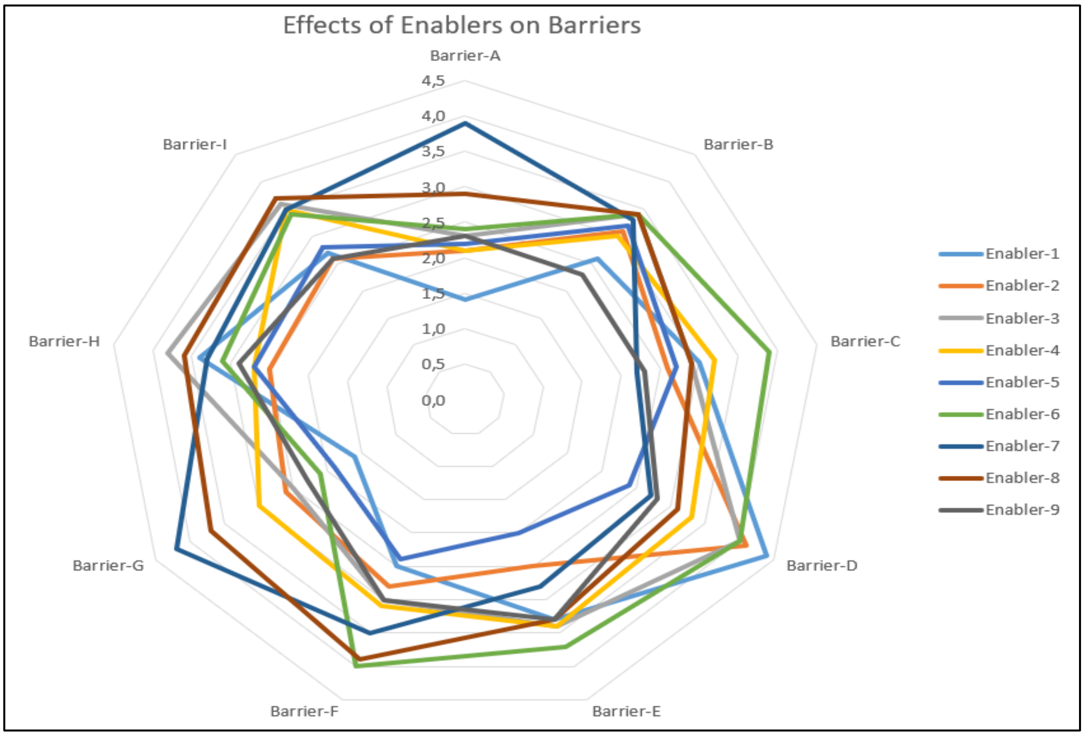

Figure 4.10. Shows the interaction between enablers and barriers of CE and BC adoption

Table 4.9. The list of enablers mentioned in Figure 4.10

Enabler-1	More immutable, secure, and private data thanks to BC
Enabler-2	More transparent supply chain traceability
Enabler-3	Improved communication (information sharing), so more collaboration and trust
Enabler-4	Enhanced innovative business models thanks to BC
Enabler-5	Low transaction costs
Enabler-6	Technical effectiveness of BC (operational efficiencies, smart contract, automation)
Enabler-7	Existence of improved new regulations and incentives
Enabler-8	Exercising and educating stakeholders (designers, building owners)
Enabler-9	Decentralization and disintermediation

Table 4.10. The list of barriers mentioned in Figure 4.10

Barrier-A	Political/Governmental challenges
Barrier-B	Economic and social challenges
Barrier-C	Technological challenges
Barrier-D	Data related challenges
Barrier-E	Blockchain performance challenges
Barrier-F	BIM and blockchain integration challenges
Barrier-G	Environmental/ Ecological challenges
Barrier-H	Ownership and liabilities-related challenges
Barrier-I	Organizational challenges

- **Enabler-1, enabler-2, enabler-3, enabler-6, and barrier-D interaction:** According to survey participants; more immutable/secure/private data environment, more transparent supply chain traceability, improved communication (information sharing), so more collaboration and trust, and finally, technical effectiveness of BC have high effects in solving problems related to data-related challenges. To illustrate, CI participants think that more immutable (resistant to tampering), secure and private data environment provided by BC has a high effect in solving data-related challenges like possible inefficiencies in providing data immutability, security, privacy, confidentiality, and availability. In addition, the immutable, secure and private data environment provided by BC paves the way for more transparent and traceable supply chains. Therefore, the lack of transparency and traceability problem regarding CE adoption can be solved by BC adoption. However, determining the correct level of transparency, data ownership, and liability issues may cause problems among the sector participants. At this point, enabler-3 and enabler-6 take place and may provide a solution to the mentioned problems in the previous sentence. Enabler-6, the technical and operational effectiveness of blockchain (use of smart contract and increased automation), paves the way for enabler-3, improved communication, collaboration, coordination and trust. Connectedly, this enhanced communication, collaboration, coordination, and trust environment may solve the determining the correct level of transparency, data ownership, and liability issues.

- **Enabler-7 and barrier-A interaction:** Survey participants think that enabler-7 has a high effect in solving problems related to barrier A. The existence of improved new regulations and incentives may be highly efficient in solving existing political and governmental challenges.
- **Enabler-6 and barrier-C interaction:** CI participants state that the technical and operational effectiveness of blockchain (use of smart contract and increased automation) helps to overcome negative sides of technological challenges like lack of technical feasibility of blockchain usage and immaturity of blockchain technology.
- **Enabler-6 and barrier-F interaction:** The survey participants stress that the technical and operational effectiveness of blockchain (use of smart contract and increased automation) have high effects in solving problems related to BIM and blockchain integration challenges.
- **Enabler-7 and barrier-G interaction:** It is seen from the survey results that the existence of improved new regulations and incentives has a high effect in solving environmental and ecological challenges.
- **Enabler-3, barrier-H and barrier-I interaction:** According to participants, improved communication, collaboration, coordination, and trust have a high effect in solving; the lack of clarity on roles and responsibilities in BC/CE enabled system, Intellectual Property (IP), and know-how access issues in a more transparent environment. In addition, improved communication, collaboration, coordination, and trust have a high effect on solving the paradox of simultaneous competition and cooperation.
- **Enabler-8, barrier-F, barrier-G, barrier-H, barrier-I interaction:** According to the participants educating stakeholders has a high-level effect in solving; BIM and blockchain integration challenges, environmental and

ecological challenges, inertia in business to change, lack of organizational and business model readiness and, issues in a more transparent environment.

To sum up, the participants state that most of the selected enablers and barriers from the literature have a high/very high or moderate effect on the successful usage of BC and CE in the CI. There is hesitation when determining whether the enablers address the barriers; none of the participants thinks that the enablers have addressed the barriers very well (at level 5). The majority state that enablers address barriers at a moderate or high level. As a final note, as mentioned previously, every barrier against the successful usage of CE and BC in CI can also be considered a good candidate for enabler. Additionally, some suggestions to alleviate the effects of barriers are mentioned in the following section.

4.3.2.2.6 Some Suggestions to Alleviate the Effects of Barriers

Table 4.11. The list of suggestions to alleviate barriers' effects

Barriers	Suggestions to alleviate effects
Responding capacity of BC and CE (Technological capability, feasibility, immaturity, uncertainty-related problems)	Starting research and development studies and supporting these studies, starting pilot application projects, and encouraging private construction companies (tax reductions, etc.) to try BC and CE applications more.
Data-related issues (false, incomplete information entry, some cracks in security, privacy, confidentiality)	Increasing the use of technologies enhancing data production, collection, and sharing automatically, without human intervention like; RFID systems, sensors, and robots.
Determination of the appropriate level of transparency/resistance to a high level of transparency	Simply selecting the suitable BC platform and type (public-private, hybrid) for the needed work may prevent data transparency problems.

Table 4.12. The list of suggestions to alleviate barriers' effects (Continued)

Barriers	Suggestions to alleviate effects
The complexity of the blockchain (complexity of the technology to grasp). Blockchain is a new technology, so it is not well known. There are few blockchain and smart contract developers	Organizing education programs regarding BC for sector participants. Additionally, making BC usage easier may be another solution. Developing tools and applications to make BC usage easier to increase its usefulness and comfort among the users.
Legal and Contractual Uncertainty Regarding Circular Economy and Blockchain (both CE and BC are new topics, with some legal and contractual uncertainties regarding their usage)	In the first phase, governmental regulations are needed to overcome this legal and contractual uncertainty. The followings are the secondary items in solving contractual and legal uncertainties. Making modifications in construction-related contracts to integrate CE and BC concepts. Updating the procurement and tendering phases of construction projects regarding CE and BC concepts (integrating smart contracts into processes). Adding CE in contractual requirements and assigning CE experts to make easier the adoption process for CI participants. Choosing a construction project delivery method that adopts holistic project management like IPD to increase collaborative work environment which positively affects the CE adoption process.

Table 4.13. The list of suggestions to alleviate barriers' effects (Continued)

Barriers	Suggestions to alleviate effects
Operational and supply chain risks (e.g., difficulty with establishing cross-organizational collaboration and coordination, risk of codependency for different organizations or firms due to the adoption of a BC-enabled CE)	For the difficulty with establishing cross-organizational collaboration and coordination problems, the proposed solutions are making organizational structures suitable for working together and integrating BC into the daily work environment. BC increases the trust between stakeholders from different organizations and makes it possible for them to collaborate and coordinate for the same purpose. For the codependency of different organizations or firms, finding the right balance between collaboration and coopetition may be a solution.
Lack of awareness, understanding, know-how, and proper vision (unavailability of management commitment), inertia in business to change, and lack of supply chain support	Exercising and educating CI managers and stakeholders (designers and building owners). Organizing public campaigns to increase awareness. Architects, engineers, and contractors should be required to complete CE and BC training as part of their professional license requirements. To overcome the inertia in businesses and lack of supply chain support regarding the adoption of CE and BC in CI, education, incentives, and successful business examples may be triggering items.

Table 4.14. The list of suggestions to alleviate barriers' effects (Continued)

Barriers	**Suggestions to alleviate effects**
Existing infrastructure-related problems (BC requires stable and fast internet access and bandwidth, and connectivity is a challenge in that sense. This also prevents successful usage of BC in CE)	Making investments and enhancements in information and communication technology to reach desired service level.
Lack of governmental incentives	Initially, the policy decision-makers should be educated and aware of these CE and BC concepts and their possible advantages when they are integrated into CI. They should be convinced that adopting and using CE and BC in CI brings community benefits. The incentives should be claimed based on applicable projects comprising CE and BC adoption.

Within the scope of this chapter, the findings (enablers and barriers lists) gathered from the literature review and the survey results are demonstrated and discussed. Several suggestions to alleviate the effects of barriers regarding CE and BC adoption in CI are presented. In the next chapter, the conclusions and recommendations for future studies are presented.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the summary and conclusion of the paper. Firstly, an overview of the study is presented. Secondly, the study's contribution is discussed. Next, the limitations of the study are discussed. Finally, the chapter concludes with future research recommendations.

5.1 Summary

The construction industry (CI) is material-intensive and requires considerable material exploitation in its different phases and areas. Such a massive amount of consumption results in some undesired effects. The mentioned effects are the overall summation of attempts made between periods starting from the cradle of any material to the gate. In this cradle-to-gate process, a significant part of all executed works is linear; take, make, and dispose of. Hence, the circular economy (CE) concept has emerged to alleviate these undesired effects by shifting the linear processes to circular ones. In this manner, the adoption and successful implementation of the circular economic model are of great importance both in the general business world and, particularly, in the CI.

The CI has a remarkable share in the emergence of undesired effects on the environment. Therefore, a successful shift to the CE in the CI can significantly contribute to meaningful reductions in gas emissions, mass material usage, waste generation, and the expected rise in average global temperature. Connectedly, technological advancements, especially the developments in blockchain (BC) technology, have catalyst impacts on the adoption and successful employment of the CE.

Therefore, the integration of BC into the CI over the CE has a constructive effect on the operation of the industry. On the other hand, integrating BC with the CE raises some barriers to adoption and implementation. The CI has a remarkable share in the emergence of undesired effects on the environment. Therefore, a successful transition to the CE in the CI can significantly contribute to meaningful reductions in gas emissions, mass material usage, waste generation, and the expected rise in average global temperature.

Since the BC-enabled CE is in its infancy, such awareness should be improved before a wide range of industries, including CI, can implement it. Additionally, as mentioned earlier, the transition to the BC-enabled CE has both challenges and drivers. Hence, for a decent adoption and application of the BC-enabled CE, interested stakeholders should be aware of this new concept and quietly understand its dynamics (e.g., barriers and enablers).

Therefore, a literature review was performed to determine barriers and enablers of BC and CE concepts. As a result of the literature review, 122 sub-barriers and 29 enablers were identified. The identified barriers and enablers were categorized based on the TOE framework. Additionally, the 122 sub-barriers were collected under 29 general barrier titles for the sake of simplicity in the survey study.

The survey study was conducted to evaluate the awareness level of the construction and many other construction-related sector professionals in terms of BC, CE concepts, and their enablers and barriers. The ideas of professionals were collected regarding the barriers and enablers filtered through the literature search. Finally, the determined barriers, enablers, and survey results were discussed in the discussion chapter regarding the CI perspective.

To sum up, on average, sector participants' awareness level regarding CE is slightly more than BC. The enablers and barriers mentioned in the literature are mostly seen as effective regarding the successful implementation of CE and BC concepts in CI. Based on the data gathered from CI participants, CE and BC concepts are mostly used in academic studies and have not diffused to practice yet. The reasons include the cost of implementation, lack of incentivization, and risk-averse behavior of sector participants. Due to the lack of successful business examples, the adoption process requires some trial-and-error and education processes, which are costly and requires incentivization.

Finally, lack of sector awareness, BC and CE experienced stakeholders, lack of sufficient incentivization, inherent properties of CI, and difficulties in changing settled habits are prominent barriers to the adoption of CE and BC in the CI. Educating sector participants, increased governmental incentives, and new effective regulations are the primary enablers of the adoption of CE and BC in CI.

5.2 Contributions of the Study

This research contributes to the current body of knowledge in several ways. The general view of the collocated use of the CE and BC in the CI is explained in detail. Current awareness levels and perspectives of academia and industry professionals regarding CE and BC adoption and usage in the CI are portrayed via a survey study. The barriers and enablers of using BC and CE, which are grounded in the TOE framework, help understand the dynamics of this adoption process in the construction industry.

5.3 Limitations of the Study

Difficulty in finding a construction company that adopted both CE and BC in their business models prevented the investigation of the topic on real cases. Hence, this study was limited to exploring enablers and barriers through a survey. Moreover, BC and CE are contemporary terms, and the knowledge about these concepts was low. Therefore, a limited number of participants could be reached for the survey study. The survey participants' knowledge levels were also at low levels, and this is a limitation of the study regarding the survey questions requiring a good level of CE and BC knowledge.

5.4 Recommendations for Future Works

Empirical studies are needed to investigate the enablers and barriers of using BC-enabled CE in real-life projects. Moreover, since the construction industry is fragmented in terms of company sizes (e.g., small, medium, large), project types (e.g., cement production, building renovation, infrastructure construction), stakeholders (e.g., design consultancy, contractor), and geographical locations (e.g., Europe, USA), the effect of such factors would vary. Further research is needed to observe the changes in the enablers and barriers of adoption under different circumstances.

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APPENDICES

A. Lists of Barriers

Table A.1. List of technological barriers to CE-BC

	Challenges	Sub-challenges	Scope	Authors
TECHNOLOGICAL BARRIERS	Responding capacity (capability, maturity)	Technological capability/feasibility/immaturity/ Uncertainty	BC-CE	(Huang, Zhen, Wang, & Zhang, 2022) , (AlShamsi, Al-Emran, & Shaalan, 2022) ,(Rejeb, Rejeb, Keogh, & Zailani, 2022)
		Time required by many implementation activities related to technology adoption	BC-CE	(Santana,Ribeiro, 2022) , (Chaudhuri, Subramanian, & Dora, 2022)
	Business Use Cases	Extending RFID systems to the supply chain partners and assuring the sustainability of RFID systems /Accuracy and effectiveness of RFID systems	CE	(Santana,Ribeiro, 2022)
		Brand image (company reputation) / damaged by third-party renovation regarding repaired or recovered products	CE	(Bressanelli, Perona, & Saccani, 2019)
		Technological challenges to separate materials/Difficulties in making product disassembly operation easier and safe during the reverse chain	CE	(Erol, et al., 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021)
	Existing infrastructure (e.g., current systems not supporting reuse or smart demolition, and the need to enhance communication networks to enable blockchain integration)	Existing systems may be barriers to implementing Blockchain technology / Circular Economy (CE)	BC-CE	(Rejeb, Rejeb, Keogh, & Zailani, 2022) (Huang, Zhen, Wang, & Zhang, 2022) (Magrini, et al., 2021) (Santana,Ribeiro, 2022) (Teisserenc & Sepasgozar, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Chaudhuri, Subramanian, & Dora, 2022) (Elghaish, et al., 2022)
		A fragmented and costly method of demolition	BC-CE	
		Difficulty to reuse existing blockchain network due to the one-off nature of construction project	BC-CE	
		Need to enhance existing communication networks	BC	
		Continuous development poses significant issues for integrating blockchain with legacy systems	BC	
		Bandwidth and connectivity requirements for BCT (stable and fast internet access)	CE	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Teisserenc & Sepasgozar, 2021)
	Blockchain limitations and requirements (e.g., data storage limitations of blockchain, difficulties in providing the needed high computing power for blockchain usage)	Higher requirements of BCT for computing equipment	BC	(Teisserenc & Sepasgozar, 2021) (Huang, Zhen, Wang, & Zhang, 2022) (Kouhizadeh, Zhu, & Sarkis, 2020) (Magrini, et al., 2021) (Teisserenc & Sepasgozar, 2021) (Rejeb, Rejeb, Keogh, & Zailani, 2022)
		Blockchain requires specific IT infrastructure	BC	
		Storage capacity requirements for BCT	BC	

Table A.2. List of technological barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
TECHNOLOGICAL BARRIERS	Data-related issues (e.g., security, privacy, confidentiality)	Data security, privacy /confidentiality, availability, integrity, anonymity	BC-CE	(Teisserenc & Sepasgozar, 2021) (Shojaei, et al., 2021) (Choo, Ozcan, Dehghantanha, & Dehghantanha, 2020) (AlShamsi, Al-Emran, & Shaalan, 2022) (Kumar, Chopra, 2022) (Demestichas & Daskalakis, 2020) (Kouhizadeh, Zhu, & Sarkis, 2020) (Shojaei, Wang, & Fenner, 2020) (Teisserenc & Sepasgozar, 2021) (Wang, Singgih, Wang, & Rit, 2019) (Dwivedi & Paul, 2022) (Khan, Shah, Yu, & Tanveer, 2022) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böckel, Nuzum, & Weissbrod, 2021) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Huang, Zhen, Wang, & Zhang, 2022),(Böhmecke-Schwafert, Wehinger, & Teigland, 2022),(Magrini, et al., 2021);(Govindan, 2022),(Santana,Ribeiro, 2022),(Erol, et al., 2021),(Feng, Laî, Zhu, 2022), (Bressanelli, Perona, & Saccani, 2019)
		Security and tamper proof requirements for the industry/ Resilience against cyber-attacks is required in the industry / Risk of cyber confrontations / Cyber security risks / Malicious attacks/hacking of IoT /Resilience against combined attacks is a challenge for BCT and IoT	BC-CE	(Teisserenc & Sepasgozar, 2021) (Govindan, 2022) (Kouhizadeh, Zhu, & Sarkis, 2020) (Wang, Singgih, Wang, & Rit, 2019) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Dwivedi & Paul, 2022)
		Lack of management and security of information shared within the supply chain	BC-CE	
		Data ownership-Authentication and trustworthiness of the data/ False-Incomplete information being entered in the blockchain	BC	(Teisserenc & Sepasgozar, 2021) (Böckel, Nuzum, & Weissbrod, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Demestichas & Daskalakis, 2020) (Shojaei, et al., 2021) (Shojaei, Wang, & Fenner, 2020) (Wang, Singgih, Wang, & Rit, 2019) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Magrini, et al., 2021)
		Data interoperability for information sharing / Lack of adequate collaboration and information sharing /and suitable platforms for them	BC-CE	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Kumar, Chopra, 2022) (Kouhizadeh, Zhu, & Sarkis, 2020) (Shojaei, et al., 2021) (Teisserenc & Sepasgozar, 2021) (Khan, Shah, Yu, & Tanveer, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Magrini, et al., 2021) (Bressanelli, Perona, & Saccani, 2019)

Table A.3. List of technological barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
TECHNOLOGICAL BARRIERS	Traceability, transparency and immutability issues	Need for traceability, visibility and transparency of information/components and immutable audit trails to track and trace	BC-CE	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Shojaei, et al., 2021) (Magrini, et al., 2021) (Santana,Ribeiro, 2022) (Bressanelli, Perona, & Saccani, 2019)
		Lack of transparency and traceability in the (construction) supply chain because of the high number of participants and short timeframes/material flow and supplier collaboration	CE	(Kouhizadeh, Zhu, & Sarkis, 2020), (Erol, et al., 2022), (Teisserenc & Sepasgozar, 2021) (Magrini, et al., 2021)
		The challenging key issue in the implementation of a circular economy is ensuring coordination, control and transparency within a network of parties.	BC-CE	(Santana,Ribeiro, 2022) (Chaudhuri, Subramanian, & Dora, 2022)
		Determination of the appropriate level of transparency / Resistance to a high level of transparency among supply chain actors	BC-CE	(Kouhizadeh, Zhu, & Sarkis, 2020) (Wang, Singgih, Wang, & Rit, 2019)
		Lack of real-time/rapid and high-volume information	BC-CE	(Teisserenc & Sepasgozar, 2021) (Kouhizadeh, Zhu, & Sarkis, 2020) (Erol, et al., 2022) (Magrini, et al., 2021) (Erol, et al., 2021)
		Lack of technology to track products	BC-CE	
	Blockchain compatibility, availability, and interoperability challenges	Lack of tools and apps for blockchain integration	BC	(Govindan, 2022) (Shojaei, et al., 2021)
		BCT has a low throughput compared to centralized databases/ High latency of BCT	BC-CE	(Shojaei, et al., 2021) (Teisserenc & Sepasgozar, 2021) (Kouhizadeh, Zhu, & Sarkis, 2020) (Wang, Singgih, Wang, & Rit, 2019) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Magrini, et al., 2021) (Erol, et al., 2021) (Kumar, Chopra, 2022)
		Blockchain interoperability/ Usage of different digital tools: interoperability issues	BC-CE	
		Lack of scalability of BCT / Blockchain scalability trilemma: trade-off between scalability, decentralization, and security	BC	(Teisserenc & Sepasgozar, 2021) (Kouhizadeh, Zhu, & Sarkis, 2020) (Choo, Ozcan, Dehghantanha, & Dehghantanha, 2020)
		Data storage limitations on the blockchain	BC	(Shojaei, Wang, & Fenner, 2020) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Kumar, Chopra, 2022) (Teisserenc & Sepasgozar, 2021)
		Blockchain network access challenges (permissioned or permission-less) / Choice between public or private blockchain	BC	(Teisserenc & Sepasgozar, 2021) (Shojaei, Wang, & Fenner, 2020) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Govindan, 2022)
		Loop activity is also the one with the least supported blockchain activities	BC-CE	(Kouhizadeh, Zhu, & Sarkis, 2020) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022)
		Proof-of-work (PoW) i.e., mining is not energy efficient	BC-CE	(Shojaei, Wang, & Fenner, 2020) (Kouhizadeh, Zhu, & Sarkis, 2020) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böckel, Nuzum, & Weissbrod, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022)

Table A.4. List of technological barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
TECHNOLOGICAL BARRIERS	The complexity of blockchain (e.g., Difficulty to develop new blockchain consensus mechanisms / Complexity of the technology to grasp)	Difficulty to develop new blockchain consensus mechanisms / Complexity of the technology to grasp/ Introducing blockchains may overcomplicate the existing supply chain ecosystem / CE ecosystem / Difficulty to code smart contracts/ Challenge to program bug-free smart contracts which are permanently stored on the blockchain/ Development of efficient algorithms	BC	(Teisserenc & Sepasgozar, 2021), (Rejeb, Rejeb, Keogh, & Zailani, 2022), (Wang, Singgih, Wang, & Rit, 2019), (Böckel, Nuzum, & Weissbrod, 2021),(Huang, Zhen, Wang, & Zhang, 2022), (Böhmecke-Schwafert, Wehinger, & Teigland, 2022), (Magrini, et al., 2021)
	Ownership and liability issues (e.g., unclear roles, responsibilities, intellectual property)	Difficulty to prove intellectual property rights (ownership, immutability) / Intellectual Property (IP) and know-how access /Lack of technology transfers from the inventor to a secondary user	BC	(Teisserenc & Sepasgozar, 2021) (Dulia, Ali, Garshasbi, & Kabir, 2021) (Teisserenc & Sepasgozar, 2021) (Wang, Singgih, Wang, & Rit, 2019) (Bressanelli, Perona, & Saccani, 2019) (Dulia, Ali, Garshasbi, & Kabir, 2021)
		Lack of clarity on roles and responsibilities / Lack of enforceability is a key challenge as it is very difficult to know who to hold accountable	CE-BC	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Khan, Shah, Yu, & Tanveer, 2022)
	Contractual issues and uncertainty	Legal and contractual uncertainty	BC-CE	(Teisserenc & Sepasgozar, 2021) (Kouhizadeh, Zhu, & Sarkis, 2020) (Choo, Ozcan, Dehghantanha, & Dehghantanha, 2020) (Dwivedi & Paul, 2022)
	BIM and blockchain integration challenges (e.g., difficulty in tracking changes in BIM, lack of storage and scalability, legal uncertainty)	Difficulty to track changes in BIM models	BC	(Figueiredo, Hammad, Haddad, & Tam, 2022) (Teisserenc & Sepasgozar, 2021)
		BIM is not concentrated on confidentiality, non-repudiation, traceability, provenance tracking and data ownership	BC	
		Attacks from the BIM central operator cannot be recorded and tracked	BC	
		Data coming from BIM models require high computational power to be added to the blockchain network	BC	(Figueiredo, Hammad, Haddad, & Tam, 2022) (Teisserenc & Sepasgozar, 2021)
		Blockchain cannot scale in terms of storage for BIM data, it can only record the digital proof	BC	(Teisserenc & Sepasgozar, 2021)
		BIM model information is currently stored in data silos containing different models' versions/ The data value chain in the CI is still fragmented in data silos which limits collaboration and data sharing	BC	(Teisserenc & Sepasgozar, 2021)
		Lack of storage and scalability of BCT to run the BIM model entirely on BCT as a decentralized application	BC	
		Difficulty to achieve confidentiality with BCT	BC	

Table A.5. List of organizational barriers to CE-BC

	Challenges	Sub-challenges	Scope	Authors
ORGANIZATIONAL BARRIERS	Operational and supply chain risks (e.g., Difficulty with establishing cross-organizational collaboration and coordination, risk of codependency for different organizations or firms)	Potential to be used in illicit activities	BC	(Rejeb, Rejeb, Keogh, & Zailani, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021)
		Difficulty with establishing cross-organizational collaboration and coordination	BC-CE	(Erol, et al., 2022) (Shojaei, et al., 2021) (AlShamsi, Al-Emran, & Shaalan, 2022) (Feng, LaĬ, Zhu, 2022) (Bressanelli, Perona, & Saccani, 2019) (Dulia, Ali, Garshasbi, & Kabir, 2021)
		The time and labour-intensive nature of deconstruction increase the project costs and delay the schedule	-	(Elghaish, et al., 2022)
		Using blockchain in a circular economy environment may cause an increased risk of codependency for different organizations or firms	BC-CE	(Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021)
		Uncertainty about quantity, mix, quality, time and place of returns of end-of-use products	CE	(Bressanelli, Perona, & Saccani, 2019) (Dulia, Ali, Garshasbi, & Kabir, 2021)
		Circular products are designed to last, rather than for use-and-throw-away: thus, they might be unable to respond to fashion and any need changes	CE	(Bressanelli, Perona, & Saccani, 2019)
		Poor supply chain management/Supply chain inefficiencies	CE	(Teisserenc & Sepasgozar, 2021) (Khan, Shah, Yu, & Tanveer, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021)
	Inertia in business to change (e.g., absence of organizational policies to adopt blockchain and circular economy)	Firms need to configure (shift) their business models and revisit how they provide products, and services / (decentralizing their organization)/the cost of this change	BC-CE	(Rejeb, Rejeb, Keogh, & Zailani, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Santana,Ribeiro, 2022) (Erol, et al., 2021) (Hilario da Silva & Sehnem, 2022)
		The deployment of blockchain in sustainable supply chains can be hampered by issues in changing corporate culture	BC-CE	(Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022)
		Absence of organizational policies to adopt blockchain	BC	(Rejeb, Rejeb, Keogh, & Zailani, 2022)
		The need to change business processes prior to technology implementation	BC-CE	(Santana,Ribeiro, 2022) (Feng, LaĬ, Zhu, 2022) (Hilario da Silva & Sehnem, 2022) (Figueiredo, Hammad, Haddad, & Tam, 2022)

Table A.6. List of organizational barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
ORGANIZATIONAL BARRIERS	Financial resources-related issues (high purchasing, implementation, (upfront) investment, material costs, and in return uncertain revenues)	High purchasing, implementation, (upfront) investment, material cost/The higher price of environmentally friendly materials (The higher price difference between recycled products and virgin products)	BC-CE	(Teisserenc & Sepasgozar, 2021) (Feng, LaĪ, Zhu, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021) (Erol, et al., 2022) (Wang, Singgih, Wang, & Rit, 2019) (Dwivedi & Paul, 2022) (Khan, Shah, Yu, & Tanveer, 2022) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Elghaish, et al., 2022) (Govindan, 2022) (Bressanelli, Perona, & Saccani, 2019) (Santana,Ribeiro, 2022) (Kumar, Chopra, 2022)
		Digital technologies adoption must consider the operating and adoption cost/ A time mismatch between revenue and cost streams / Digital technologies adoption must consider the increased energy cost	BC-CE	(Feng, LaĪ, Zhu, 2022) (Bressanelli, Perona, & Saccani, 2019)
		Since being an early-stage market, the uncertainty of revenues (market uncertainty) and suitable business models complicate adopting blockchain CE innovation.	BC-CE	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Govindan, 2022)
		Unwillingness to take initiative, to invest in new, unproven, and high-cost technologies / Scarcity of commercial applications	BC-CE	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Govindan, 2022) (Erol, et al., 2022) (Khan, Shah, Yu, & Tanveer, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Kouhizadeh, Zhu, & Sarkis, 2020) (Dwivedi & Paul, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Kumar, Chopra, 2022) (Ghosh, Edwards, & Hosseini, 2020) (Teisserenc & Sepasgozar, 2021) (Huang, Zhen, Wang, & Zhang, 2022) (Magrini, et al., 2021) (Santana,Ribeiro, 2022)
		Little evidence of financial or environmental benefits/ Low economic benefits or (in the short run)	BC-CE	
		Lack of knowledge on cost and resources to implement due to very limited real-life examples and studies/ Lack of successful business models	BC-CE	(Dwivedi & Paul, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Govindan, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021)
		Secondary material markets not supporting CE principles / Insufficient market demand /Uncertain demand for recovered products	CE	(Erol, et al., 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Shojaei, et al., 2021) (Elghaish, et al., 2022) (Magrini, et al., 2021) (Govindan, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021)

Table A.7. List of organizational barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
ORGANIZATIONAL BARRIERS	Lack of awareness (unavailability of management commitment, absence of corporate strategy)	Unavailability of management commitment /Top management commitment / Immature management practices	BC-CE	(Mojumder & Singh, 2021) (Dwivedi & Paul, 2022) (Khan, Shah, Yu, & Tanveer, 2022) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Elghaish, et al., 2022) (Govindan, 2022) (Erol, et al., 2021) (Feng, Laİ, Zhu, 2022) (Bressanelli, Perona, & Saccani, 2019)
		Slow decision-making and implementation processes hinder blockchain CE innovation	BC-CE	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022)
		Blockchain concept and its application require nuanced investigation in different contexts	BC	(Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Kouhizadeh, Zhu, & Sarkis, 2020)
		Absence of shared goals among business partners / Absence of corporate strategy on green issues / Lack of strategic orientation	CE	(Mojumder & Singh, 2021) (Dwivedi & Paul, 2022)

Table A.8. List of organizational barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
ORGANIZATIONAL BARRIERS	Organizational and Business Model readiness (infancy of current models on blockchain and circular economy, lack of knowledge on intricacies and ramifications)	Constraints posed by a company business model	BC-CE	(Santana,Ribeiro, 2022) (Bressanelli, Perona, & Saccani, 2019)
		Centralized organizational structure / Strong industrial focus on linear business models	CE	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Bressanelli, Perona, & Saccani, 2019)
		The paradox of simultaneous competition and cooperation	BC-CE	(Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022)
		Insufficient knowledge of the system architecture, technology implementation, and application scenarios affects CSCM managers	BC-CE	(Huang, Zhen, Wang, & Zhang, 2022)
		Infancy and accessibility of blockchain /Blockchain technology in the built environment sector is still in its infancy / General uncertainty as to whether blockchain truly fits circular economy needs. The question "Is blockchain really needed?" is not answered clearly	BC	(Shojaei, et al., 2021) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Shojaei, Wang, & Fenner, 2020) (Wang, Singgih, Wang, & Rit, 2019) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Figueiredo, Hammad, Haddad, & Tam, 2022) (Böckel, Nuzum, & Weissbrod, 2021)
		Many people do not know blockchain's intricacies and ramifications. This makes it difficult for the entire supply chain to adopt the technology because it includes many new terms such as public key, private key, and cryptography	BC	(Huang, Zhen, Wang, & Zhang, 2022)
		Organizations find it challenging to keep pace with the evolution of digital technologies-difficult to track technological evolution/Difficulties in upgrading technology	BC-CE	(Dwivedi & Paul, 2022), (Rejeb, Rejeb, Keogh, & Zailani, 2022) , (Khan, Shah, Yu, & Tanveer, 2022)
		CE / Blockchain implementation requires organizational readiness / intra and inter-organizational relationships	BC-CE	(Shojaei, et al., 2021) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Huang, Zhen, Wang, & Zhang, 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Hilario da Silva & Sehnem, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021)

Table A.9. List of environmental barriers to CE-BC

	Challenges	Sub-challenges	Scope	Authors
ENVIRONMENTAL BARRIERS	Uncertain and insufficient regulations / Need for new regulations including contemporary topics such as digitalization, reuse and repair and decentralized business models	Uncertain/poor regulations and compliance / Insufficient law implementation	BC-CE	(Teisserenc & Sepasgozar, 2021) (Kumar, Chopra, 2022) (Demestichas & Daskalakis, 2020) (Erol, et al., 2022) (Kouhizadeh, Zhu, & Sarkis, 2020) (Wang, Singgih, Wang, & Rit, 2019) (Khan, Shah, Yu, & Tanveer, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böckel, Nuzum, & Weissbrod, 2021) (Elghaish, et al., 2022) (Magrini, et al., 2021) (Govindan, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022)
		Existing regulations and codes hinder the reuse and repair	CE	
	Lack of know-how, proper vision and incentives regarding CE/BC of policy decision-makers and governments	Lack of clear incentives/governmental support	CE-BC	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Kouhizadeh, Zhu, & Sarkis, 2020) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Erol, et al., 2021) (Bressanelli, Perona, & Saccani, 2019) (Dulia, Ali, Garshasbi, & Kabir, 2021)
		Lack of proper vision such as goals, objectives, targets, and indicators in regard to the circular supply chain	CE	(Dulia, Ali, Garshasbi, & Kabir, 2021)
		Lack of policymaker support creates challenges for organizations implementing blockchain CE innovation. (i.e., Funding and relevant regulations)	CE-BC	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Govindan, 2022) (Erol, et al., 2021)
		Lack of CE know-how of political decision-makers	CE	(Erol, et al., 2022)
	Lack of supply chain support	Availability of suitable supply chain partners	CE	(Bressanelli, Perona, & Saccani, 2019)
		The presence of an informal system is a challenge for CE/BCT	CE-BC	(Magrini, et al., 2021) (Govindan, 2022) (Bressanelli, Perona, & Saccani, 2019)
	Sustainability vs profit paradox (market barrier, sustainability not being a success indicator)	Measures, metrics, indicators (CE requires shifting focus from a purely volume-driven economic view to a more comprehensive one, encompassing economic, environmental, and social dimensions)/ Tensions between sustainability and profit objectives are a market barrier that hinders blockchain CE innovation	CE	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Bressanelli, Perona, & Saccani, 2019)
		Market cannibalization (the longer product lifecycle thanks to 'design-to-last' practices or predictive maintenance leads to a lower product substitution rate than in the linear economy)	CE	(Bressanelli, Perona, & Saccani, 2019)

Table A.10. List of environmental barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
ENVIRONMENTAL BARRIERS	Lack of awareness and understanding of blockchain and circular economy	Lack of awareness, knowledge (Proficiency/expertise) and skills regarding BCT/CE sustainability/new technologies /life cycle costs and benefits	CE-BC	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Shojaei, et al., 2021) (Wang, Singgih, Wang, & Rit, 2019) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böckel, Nuzum, & Weissbrod, 2021) (Huang, Zhen, Wang, & Zhang, 2022) (Elghaish, et al., 2022) (Govindan, 2022) (Santana,Ribeiro, 2022) (Erol, et al., 2021) (Feng, LaÏ, Zhu, 2022) (Chaudhuri, Subramanian, & Dora, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021)
		Workforce size and demographics /Lack of digital skills/ limited digital literacy/ Initial learning curves/ Dysfunctional training	BC-CE	(Teisserenc & Sepasgozar, 2021) (Shojaei, et al., 2021) (Dwivedi & Paul, 2022) (Khan, Shah, Yu, & Tanveer, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Huang, Zhen, Wang, & Zhang, 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Santana,Ribeiro, 2022) (Chaudhuri, Subramanian, & Dora, 2022)
		Absence of employee commitment	CE-BC	(Mojumder & Singh, 2021) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Bressanelli, Perona, & Saccani, 2019)
		Lack of awareness of blockchain risk (difficulty in balancing blockchain's benefits with its negative sides)	BC	(Govindan, 2022) (Elghaish, et al., 2022) (Dwivedi & Paul, 2022)
	Changing settled habits ideas/cultures (resistance to changing traditional processes)	Cultural habits in the construction industry /Changing people's mindset are a hurdle/ Slow adoption of new technologies by the construction industry	CE-BC	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Shojaei, et al., 2021) (Ghosh, Edwards, & Hosseini, 2020) (Wang, Singgih, Wang, & Rit, 2019) (Elghaish, et al., 2022) (Bressanelli, Perona, & Saccani, 2019) (Figueiredo, Hammad, Haddad, & Tam, 2022)
		Cultural issues (linear mindset)- Internal resistance to change, especially given the prevailing linear mindset and structures in industries (also referred to as the 'Linear lock-in')	CE-BC	(Bressanelli, Perona, & Saccani, 2019)
		Reluctancy / Unwillingness of sharing critical information with other parties	CE-BC	(Khan, Shah, Yu, & Tanveer, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Upadhyay, Mukhuty, Kumar, & Kazancoglu, 2021) (Govindan, 2022) (Kouhizadeh, Zhu, & Sarkis, 2020)
		Resistance to organizational and processes changes/ Lack of readiness for adoption of new technologies/Risk-averse behaviour	CE-BC	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Khan, Shah, Yu, & Tanveer, 2022) (Kouhizadeh, Zhu, & Sarkis, 2020) (Shojaei, et al., 2021) (Wang, Singgih, Wang, & Rit, 2019) (Elghaish, et al., 2022) (Bressanelli, Perona, & Saccani, 2019) (Ghosh, Edwards, & Hosseini, 2021) (Govindan, 2022) (Chaudhuri, Subramanian, & Dora, 2022)
	Lack of community support and customer readiness	CE initiatives cannot sufficiently benefit social values through job creation and expansion	CE	(Kouhizadeh, Zhu, & Sarkis, 2020) (Dulia, Ali, Garshasbi, & Kabir, 2021)

Table A.11. List of environmental barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
ENVIRONMENTAL BARRIERS	Industry characteristics (e.g., lack of industry-specific procedures, structural fragmentation of the industry)	Difficulty and cost of implementing item-level tracking and tracing	CE-BC	(Santana,Ribeiro, 2022) (Bressanelli, Perona, & Saccani, 2019)
		CE would drastically increase transportation activities and costs if all the products have to be sent back to producers or specialized sites for refurbishing, remanufacturing, etc.	CE	
		The recycling of building materials is often a labour-intensive process	CE	(Shojaei, et al., 2021)
		Lack of collaboration and lack of improvement culture / Lack of Coopetition/lack of trust in data governance	CE-BC	(Teisserenc & Sepasgozar, 2021) (Erol, et al., 2022) (Kouhizadeh, Zhu, & Sarkis, 2020) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Bressanelli, Perona, & Saccani, 2019) (Dulia, Ali, Garshasbi, & Kabir, 2021) (Demestichas & Daskalakis, 2020)
		Lack of industry-specific procedures	CE	(Dwivedi & Paul, 2022)
		Structural fragmentation of the industry	BC	(Teisserenc & Sepasgozar, 2021)
	The complexity of the recycling process, inefficient design routes for recovery products	There is no guarantee that the buildings or products designed for deconstruction will actually be reused.	CE	(Shojaei, et al., 2021) (Elghaish, et al., 2022)
		Lack of proper safety for workers during the recycling of hazardous materials	CE	(Dulia, Ali, Garshasbi, & Kabir, 2021)
		The proliferation (rapid increase) of new materials as well as the growth of product complexity increase the difficulties in managing to recover and recycle processes	CE	(Bressanelli, Perona, & Saccani, 2019)
	Lack of information regarding provenance, unfinished parts of materials/ Tracking difficulties of materials through their lifecycle	Lack of information about the provenance of material / Tracing raw materials and unfinished parts in some sectors	CE	(Chaudhuri, Subramanian, & Dora, 2022) (Dulia, Ali, Garshasbi, & Kabir, 2021)
		Lack of information concerning a product's lifecycle /Loss of user's control over products /Broken information flow across lifecycle phases is a challenge for DT that can be addressed by BCT	CE	(Bressanelli, Perona, & Saccani, 2019) (Santana,Ribeiro, 2022) (Chaudhuri, Subramanian, & Dora, 2022)
		Lack of standardization and transportability of salvaged building components / The difficulties in estimating the salvage value of building elements / Lack of data about availability, quality and quantity of salvaged building components	CE	(Elghaish, et al., 2022) (Bressanelli, Perona, & Saccani, 2019)
		The long lifespan of buildings **(building components*)** and the involvement of multiple sectors (e.g., design, construction, operation, maintenance, renovation) limit the capability of information tracking and value chain maintenance	CE	(Shojaei, et al., 2021) (Magrini, et al., 2021)

Table A.12. List of environmental barriers to CE-BC (Continued)

	Challenges	Sub-challenges	Scope	Authors
ENVIRONMENTAL BARRIERS	Lack of awareness and uncertainty in life cycle thinking	Lack of consumer knowledge about reused components	CE	(Dulia, Ali, Garshasbi, & Kabir, 2021) (Teisserenc & Sepasgozar, 2021)
		Uncertainties at the products' end of life and quality assurance throughout the life cycle of a product /Quality degradation of recycled products	CE	(Bressanelli, Perona, & Saccani, 2019)
	The environmental and ecological burden of blockchain	Energy consumption of BCT	BC-CE	(Teisserenc & Sepasgozar, 2021) (Shojaei, Wang, & Fenner, 2020) (Erol, et al., 2022) (AlShamsi, Al-Emran, & Shaalan, 2022) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böckel, Nuzum, & Weissbrod, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022)
		Materials waste in the industry/ Lack of biodegradable resources in circular supplies	CE	(Dulia, Ali, Garshasbi, & Kabir, 2021) (Teisserenc & Sepasgozar, 2021)
		Eco-efficiency of technological processes-Renovation processes (especially recycling) may be inefficient from a technological perspective causing losses, cross contamination of materials	CE-BC	(Bressanelli, Perona, & Saccani, 2019)
		Lack of proper tools to reliably calculate carbon footprints	CE	(Erol, et al., 2022)
		The myopic focus of existing R- strategies (Reducing, Reusing and Recycling)	CE	(Erol, et al., 2022) (Elghaish, et al., 2022)
		Lack of validity with respect to the ecological benefits of product recovery	CE	
		The act of recycling and reusing building materials is limited to the isolated efforts of particular facilities / Current buildings were not designed for disassembly	CE	(Shojaei, et al., 2021) (Elghaish, et al., 2022) (Cruz Rios, F., Grau, D., & Bilec, M.,2021)
	Standards and compliance issues (lack of standardization, legal disputes and compliance issues)	Lack of standards for blockchain	BC-CE	(Teisserenc & Sepasgozar, 2021) (Bressanelli, Perona, & Saccani, 2019) (Huang, Zhen, Wang, & Zhang, 2022) (Wang, Singgih, Wang, & Rit, 2019) (Kouhizadeh, Zhu, & Sarkis, 2020) (Choo, Ozcan, Dehghantanha, & Dehghantanha, 2020) (Rejeb, Rejeb, Keogh, & Zailani, 2022) (Böckel, Nuzum, & Weissbrod, 2021) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Govindan, 2022) (Bressanelli, Perona, & Saccani, 2019)
		Lack of standards for CE	CE	
		Blockchain technology adoption requires standardization	BC	
		Illegal use of blockchains	BC	
		Stringent standards, regulations, and certifications in the industry	BC	
		Legal disputes and compliance issues	BC	

Table A.13. List of technological enablers/drivers to CE-BC

	Drivers /Enablers	Scope	Author
TECHNOLOGICAL ENABLERS/DRIVERS	Virtualization	CE	(Khan, Shah, Yu, & Tanveer, 2022) (Erol et al.,2022)
	Information Communication Technology, Information sharing, Enhanced collaboration, Feedback-rich systems	CE-BC	(Khan, Shah, Yu, & Tanveer, 2022) (Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022)
	Choosing IPD and other collaborative project delivery methods	CE	(Cruz Rios,F.,Grau,D.,& Bilec,M.,2021)
	Big Data, data analytics, creating databases for reusable components	CE	(Khan, Shah, Yu, & Tanveer, 2022) (Cruz Rios,F.,Grau,D.,& Bilec,M.,2021)
	Industry 4.0, process digitalization, digital and 3D printing, internet of things (IoT), BIM, automation, robotics	CE-BC	(Khan, Shah, Yu, & Tanveer, 2022) (Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022)
	Immutability, building higher levels of trust in the supply chain ecosystem	BC-CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (A. Shojaei, R. Ketabi, M. Razkenari et al.,2021)
	Security, privacy	BC-CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022), (A. Shojaei, R. Ketabi, M. Razkenari et al.,2021)
	Decentralization and increased level of disintermediation	BC-CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022)
	Smart contracts	BC-CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022)
	Enhanced interoperability	BC-CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022)
	Responsible production through tamper-proof, distributed data records (less hazardous chemicals; fewer emissions)	CE-BC	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022)

Table A.14. List of technological enablers/drivers to CE-BC (Continued)

	Drivers /Enablers	Scope	Author
TECHNOLOGICAL ENABLERS/DRIVERS	Sharing platform provision (no third party, trustworthy information)	CE-BC	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022)
	Low transaction costs	BC-CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022)
	Developing and implementing material tracking technologies to increase transparency, supply chain transparency and traceability (tamper-proof, distributed data records), Tracking complex supply chains/products' lifecycle and their sustainability to support reutilizing and reusing	CE-BC	(Cruz Rios,F.,Grau,D.,& Bilec,M.,2021), (Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022) (Böhmecke-Schwafert, Wehinger, & Teigland, 2022) (Erol et al.,2022), (A. Shojaei, R. Ketabi, M. Razkenari et al.,2021)
	The blockchain platform can provide comprehensive, transparent, and reliable material traceability and information tracking not only to the materials' sources but also to their current state. By keeping track of the materials and products in each facility and their current status, proactive planning could be made for their recycling and repurposing in areas requiring such products.	CE-BC	(A. Shojaei, R. Ketabi, M. Razkenari et al.,2021)
	Finding the right balance between economic, environmental, logistics and organizational criteria more easily with the help of the blockchain network	CE-BC	(A. Shojaei, R. Ketabi, M. Razkenari et al.,2021)
	Resilience even if one entity fails or is unable to execute.	CE-BC	(A. Shojaei, R. Ketabi, M. Razkenari et al.,2021)

Table A.15. List of environmental and organizational enablers/drivers to CE-BC

	Drivers /Enablers	Scope	Author
ORGANIZATIONAL ENABLERS/DRIVERS	Stakeholder engagement: exercising leadership and educating stakeholders (e.g., designers, building owners), supplier training	CE	(Khan, Shah, Yu, & Tanveer, 2022) (Cruz Rios,F.,Grau,D.,& Bilec,M.,2021)
	Top management commitment, better knowledge management and improved decision making	CE-BC	(Khan, Shah, Yu, & Tanveer, 2022) (Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022) (Erol, Peker, Ar, Turan, & Searcy, 2021)
	Organizational culture, corporate governance, and resources	CE	(Khan, Shah, Yu, & Tanveer, 2022)
	The resolve Model (Regenerate, share, optimize, loop, virtualize, exchange) is an operational tool to guide organizations in terms of CE	CE	(Khan, Shah, Yu, & Tanveer, 2022)
	Innovative business models, increased operational efficiencies / Innovation in exploring new ways of working, new products and materials or new business models	BC-CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022) (Kanters, 2020)
	Integrating CE in contractual requirements and assigning CE consultants to help with the design	CE	(Cruz Rios,F.,Grau,D.,& Bilec,M.,2021)
	Cost sharing among stakeholders to reduce the individual cost of maintaining the CE repository	CE-BC	(A. Shojaei, R. Ketabi, M. Razkenari et al.,2021)
ENVIRONMENTAL ENABLERS/DRIVERS	Circular Product Design: slowing resource loop, enforcing sustainable procurement aligned with CE	CE	(Khan, Shah, Yu, & Tanveer, 2022) (Cruz Rios,F.,Grau,D.,& Bilec,M.,2021)
	Improved regulation, adding CE in building codes (mandatory plan for building disassembly), Reaching consensus around the concept of CE and creating explicit guidelines about different CE strategies in all sectors	CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022) (Cruz Rios,F.,Grau,D.,& Bilec,M.,2021)
	Incentivisation, increasing demolition and carbon taxes, landfill fees, increasing taxes on new construction and reducing taxes for adaptive building, raising taxes on virgin materials, allocating public funding to circular design and construction, Incentivization to use prefabrication and modular design	CE	(Rejeb, Rejeb, Keogh,Treiblmaier, & Zailani, 2022) (Cruz Rios,F.,Grau,D.,& Bilec,M.,2021) (Khan, Shah, Yu, & Tanveer, 2022)
	Client's motivation for a circular building from the beginning of the design process	CE	(Kanters, 2020)
	Improved quality of life through increased sustainability	CE-BC	(Böhmecke-Schwafert, Wehinger, & Teigland, 2022)

B. Survey Form

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

1. VOLUNTEER PARTICIPATION FORM FOR THE QUESTIONNAIRE

Ufuk ŞAHİN, a METU Civil Engineering Department graduate student, conducted this research within the scope of the master's thesis under the supervision of Faculty Member Dr. Güzide ATASOY ÖZCAN. This form has been prepared to inform you about the research conditions.

What is the Purpose of the Study?
Within the scope of this study, it is expected that the mentioned factors in the literature, which prevent and support the use of blockchain and circular economy in the construction industry, are evaluated by sector professionals.

How Do We Ask You To Help Us?
If you agree to participate in the research, you are expected to evaluate the impact of the given factors on the use of blockchain and circular economy in the construction industry on a scale of 1 to 5 and mark this choice in the field provided in the survey. Participation in this study takes an average of 15 minutes.

How Will We Use the Information We Collect From You?
Your participation in the research must be entirely voluntary. In the study, no identity or institution-identifying information is requested from you. Your answers will be kept entirely confidential and evaluated only by researchers. The data obtained from the participants will be assessed collectively and used in the thesis study.

Here's what you need to know about your participation:
This questionnaire does not contain questions that may cause personal discomfort. It does not contain a risk beyond the usual risks that are likely to be encountered in daily life. However, if you feel uncomfortable during participation due to questions or any other reason, you are free to stop and leave the study.

If you would like to receive more information about the research:
You can contact Ufuk ŞAHİN for more information about the research. E-mail: e239176@metu.edu.tr. Thank you in advance for your participation in this study.

* 1. I have read the above information and participate in this study completely voluntarily.

- ◯ Yes
- ◯ No

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

2. Demographics

* 2. About your background

- Civil Engineer
- Architecture
- Mechanical Engineer
- Electrical Engineer
- Other Fields (please specify)

* 3. About the company/institution you are working or you have worked for

- Design/Engineering Consultancy
- Contracting
- Management consultancy
- University
- Other (Please Specify)

* 4. About your department in the company/institution

- Procurement
- Tendering
- Site
- Marketing
- Design
- Progress payment
- Planning
- Other (Please Specify)

* 5. About your experience level

- Less than 5 years
- 5-10 years
- 10-15 years
- 15-20 years
- 20-30 yaears
- More than 30 years

* 6. Have you ever encountered circular economy or blockchain-oriented practice or project at any step of your professional life?

- ◯ Yes
- ◯ No
- ◯ If your answer is yes, please briefly mention the aspects of the practice.

* 7. How would you rate your knowledge level in terms of circular economy from a 0 to 5 scale? (Please drag the pointer)

0 5

* 8. How would you rate your knowledge level in terms of blockchain technology from a 0 to 5 scale? (Please drag the pointer)

0 5

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

3. Brief Explanation About Circular Economy and Blockchain technology

Circular Economy

The construction sector provides the needed foundation for the social and economic development of societies. However, the sector requires intensive use of resources such as concrete, aluminium, steel, fresh water and, wood throughout the construction and, post-construction stages. As a result of high-level resource consumption, the significant ratio of generated waste and emitted greenhouse gas on a global scale belongs to construction sector-related activities. Connectedly, the mainstream model used in the construction industry is the linear economy model depending on extracting, producing, using and finally disposing of building materials. To diminish this model's risks to society, the environment and the economy; the applicability of the circular economic model has been started to be examined. The circular economy suggests using resources in multiple cycles to gain value and decrease waste and consumption of virgin resource materials instead of demanding virgin resources continuously. It is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption. It enables key policy objectives such as

generating economic growth, creating jobs and reducing environmental impacts, including carbon emissions.

Blockchain
In its simplest form, blockchain can be described as a transparent, independent, immutable, and permanent database shared by a community across multiple locations. It is a distributed ledger and has a decentralized structure. There is no need for any intermediary third party therefore, it establishes the trust between network participants. It stores any list of transactions in a peer-to-peer network. A blockchain is a tool used to record and process transactions made in digital currency or other values (for instance, services, and products). It is used to streamline and control supply chains, construction processes, contracts, and payment approvals. The construction sector can benefit from blockchain technology in contract management, electronic document management (EDM), property management, and BIM (building information modelling). The aim is to use blockchain to keep track of all building materials and waste produced from the planning stage to the demolition stage, ensuring a more efficient information flow and positive effects on the environment and the economy.

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

4. **Technological Barriers**

* 9. How would you express your perception regarding the effects of the following barriers on the successful usage of blockchain/circular economy concepts in the construction sector? Please use a 1 to 5 Likert scale for the evaluation.
1 -----> very low effect
2 -----> low effect
3 -----> moderate effect
4 -----> high effect
5 -----> very high effect

You can select N/A if you don't want to answer or you don't have enough idea.

To illustrate, by selecting **1 (Very Low)**, you express that BT1 (blockchain and circular economy responding capacity)'s role as a barrier for adapting blockchain/circular economy in the construction sector is **Very Low.**

	N/A	1 (Very Low)	2 (Low)	3 (Moderate)	4 (High)	5 (Very High)
BT1-Responding capacity of blockchain and circular economy (technical capability, immaturity and time required by many implementation activities related to technology adoption in the construction industry)	○	○	○	○	○	○
BT2-Problems inherit in construction sector (e.g., lack of accuracy and effectiveness of RFID systems and their components in real-life environments/ Technological challenges to separate construction industry-related materials)	○	○	○	○	○	○

BT3-Existing infrastructure (e.g., current systems not supporting reuse or smart demolition, and the need to enhance communication networks to enable blockchain integration / Difficulty to reuse existing blockchain network due to the one-off nature of construction projects)

BT4-Blockchain limitations and requirements (e.g., data storage limitations of blockchain, difficulties in providing the needed high computing power for blockchain usage)

BT5-Data related issues (e.g., some cracks in security, privacy and confidentiality/insufficiency of blockchain in security and tamper-proof data requirements for the industry/ false- Incomplete information being entered in the blockchain)

BT6- Lack of transparency and traceability in the (construction) supply chain, determination of the appropriate level of transparency / Resistance to a high level of transparency

BT7-Blockchain compatibility, availability, interoperability, scalability and latency challenges (Lack of tools and apps for blockchain integration)

BT8-Complexity of the blockchain (e.g., Complexity of the technology to grasp)

BT9-Ownership and liability issues (e.g., unclear roles, responsibilities, difficulties in protecting intellectual property rights)

BT10-Legal and contractual uncertainty regarding circular economy and blockchain

BT11-BIM and blockchain integration challenges (e.g., difficulty in tracking changes in BIM, lack of storage and scalability)

BT12- Blockchain is a new technology, so it is not well known and there are few blockchain and smart contract developers

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

5. Organizational Barriers

* 10. How would you express your perception regarding the effects of the following barriers on the successful usage of blockchain/circular economy concepts in the construction sector? Please use a 1 to 5 Likert scale for the evaluation.

1 -----> very low effect
2 -----> low effect
3 -----> moderate effect
4 -----> high effect
5 -----> very high effect

<u>You can select N/A if you don't want to answer or you don't have enough idea.</u>

To illustrate, by selecting **1 (Very Low)**, you express that BO1 (Operational and supply chain risks)'s role as a barrier for adapting blockchain/circular economy in the construction sector is **Very Low**.

	N/A	1 (Vey low)	2 (Low)	3 (Moderate)	4 (High)	5 (Very High)
BO1- Operational and supply chain risks (e.g., Difficulty with establishing cross-organizational collaboration and coordination, risk of codependency for different organizations or firms due to adoption of blockchain-enabled circular economy)	○	○	○	○	○	○
BO2- Financial resources-related issues (e.g., high purchasing, implementation,(upfront) investment, material costs of circular economy/blockchain, and in return uncertain revenues)	○	○	○	○	○	○
BO3- Lack of awareness (unavailability of management commitment, absence of corporate strategy)	○	○	○	○	○	○
BO4- Inertia in business to change (e.g., absence of organizational policies to adopt blockchain and circular economy)	○	○	○	○	○	○
BO5- Organizational and business model readiness (infancy of current models on blockchain and circular economy, lack of knowledge on intricacies and ramifications)	○	○	○	○	○	○

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

6. Environmental (Exterior) Barriers

* 11. How would you express your perception regarding the effects of the following barriers on the successful usage of blockchain/circular economy concepts in the construction sector? Please use a 1 to 5 Likert scale for the evaluation.

1 -----> very low effect
2 -----> low effect
3 -----> moderate effect
4 -----> high effect
5 -----> very high effect

You can select N/A if you don't want to answer or you don't have enough idea.

To illustrate, by selecting **1 (Very Low)**, you express that BE1 (Uncertain and insufficient regulations)'s role as a barrier for adapting blockchain/circular economy in the construction sector is **Very Low**.

N/A	1 (Very Low)	2 (Low)	3 (Moderate)	4 (High)	5 (Very High)
BE1- Uncertain and insufficient regulations / Need for new regulations including contemporary topics such as digitalization, reuse and repair and decentralized business models					
◯	◯	◯	◯	◯	◯
BE2- Lack of governmental incentives					
◯	◯	◯	◯	◯	◯
BE3- Lack of supply chain support regarding the circular economy and blockchain integration (The presence of an informal system is a challenge for the circular economy and blockchain technology's successful usage/ Availability of suitable supply chain partners)					
◯	◯	◯	◯	◯	◯
BE4- Sustainability vs profit paradox (market barrier, sustainability not being a success indicator)					
◯	◯	◯	◯	◯	◯
BE5- Lack of awareness, understanding, know-how and proper vision of policy decision-makers regarding blockchain and circular economy					
◯	◯	◯	◯	◯	◯
BE6- Changing settled habits ideas/cultures (resistance to changing traditional processes)					
◯	◯	◯	◯	◯	◯
BE7- Lack of community support and customer readiness for circular economy and blockchain					
◯	◯	◯	◯	◯	◯
BE8- Construction industry characteristics (e.g., lack of industry specific procedures, structural fragmentation of the industry)					
◯	◯	◯	◯	◯	◯
BE9- Complexity of recycling process, inefficient design routes for recovery products (There is no guarantee that the building components or products designed for deconstruction will actually be reused)					
◯	◯	◯	◯	◯	◯
BE10- Lack of information regarding provenance, unfinished parts of materials/ Tracking difficulties of mateials through their lifecycle					
◯	◯	◯	◯	◯	◯
BE11- Lack of awareness and uncertainty in life cycle thinking (Uncertainties at the products' end of life and quality assurance throughout the life cycle of a product)					
◯	◯	◯	◯	◯	◯
BE12- Environmental and ecological burden of blockchain (Energy consumption of blockchain, high energy costs)					
◯	◯	◯	◯	◯	◯
BE13- Standards and compliance issues (lack of standardization, legal disputes and compliance issues regarding blockchain and circular economy, illegal use of blockchain)					
◯	◯	◯	◯	◯	◯

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

7. Enablers of Circular Economy/Blockchain

* 12. How would you express your perception regarding the effects of the following enablers on the successful usage of blockchain/circular economy concepts in the construction sector? Please use a 1 to 5 Likert scale for the evaluation.

1 -----> very low effect
2 -----> low effect
3 -----> moderate effect
4 -----> high effect
5 -----> very high effect

You can select N/A if you don't want to answer or you don't have enough idea.

To illustrate, by selecting **1 (Very Low)**, you express that enabler-E1 motivates the sector participants at a **very low level** regarding the transition to blockchain/circular economy adopted construction sector.

	N/A	1 (Very low)	2 (Low)	3 (Moderate)	4 (High)	5 (Very high)
E1- Finding the right balance between economic, environmental, logistics and organizational criteria more easily with the help of the blockchain network	○	○	○	○	○	○
E2- Enhancements in information communication technology, information sharing, collaboration and feedback-rich systems	○	○	○	○	○	○
E3- Choosing Integrated Project Delivery method or other collaborative project delivery methods in construction projects	○	○	○	○	○	○
E4- Thanks to the immutability of the blockchain environment, building higher levels of trust in the construction supply chain ecosystem	○	○	○	○	○	○
E5- Ability to make use of process digitalization, digital and 3D printing, internet of things (IoT), automation, robotics, Industry 4.0 technologies in construction domain	○	○	○	○	○	○
E6- Advances in big data and data analytics increase the usability of blockchain / creating databases for reusable components for the construction industry	○	○	○	○	○	○
E7- The blockchain platform can provide comprehensive, transparent, and reliable material traceability and information tracking not only to the materials' sources but also to their current state. By keeping track of the materials and products in each facility and their current status, proactive planning could be made for their recycling and repurposing in areas requiring such products.	○	○	○	○	○	○

E8- Advantages of using blockchain such as; decentralization, disintermediation, low transaction costs, security and privacy

E9- Resilience of blockchain environment even if one or more entities fail or are unable to execute

E10- Thanks to disruptive technologies (i.e. blockchain), new innovative business models will be developed and, it would be possible to increase operational efficiencies

E11- Integrating circular economy in contractual requirements and assigning circular economy consultants to help for design

E12- Improved regulation, adding circular economy in building codes (mandatory plan for building disassembly)

E13- Increased incentivization, creating tax deductions for circular design strategies, raising taxes on virgin materials, allocating public funding to circular design and construction, increasing taxes on new construction, reducing taxes for adaptive building

E14- Incentivization to use prefabrication and modular design since it would be easier to track components produced in a facility

E15- Client's motivation for a circular building from the beginning of the design process

E16- Improved quality of life through increased sustainability thanks to blockchain enabled circular economy

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8.

13. How would you express your perception regarding the effects of each of the following enablers on each barrier?

[Columns from 1 to 9 -----> represent enablers]
[Rows from A to I -----> represent barriers]

Please use a 0 to 5 scoring format for the evaluation.
0 -----> no effect/ no relation
1 -----> very low effect
2 -----> low effect
3 -----> moderate effect
4 -----> high effect
5 -----> very high effect

For example, If you select **1** for the intersection of barrier A and enabler 1, it means that enabler 1 (More immutable, secure and private data thanks to blockchain) has a **very low effect** in solving problems related to barrier A (Political/Governmental challenges)".

(BC/BCT: Blockchain technology, CE: Circular Economy)

	Enabler-1- More immutable (resistant to tampering), secure and private data thanks to blockchain	**Enabler-2-** More transparent supply chain traceability	**Enabler-3-**Improved communication (information sharing) so more collaboration,coordination and trust	**Enabler-4-** Enhanced innovative business models thanks to blockchain	**Enabler-5-** Low transaction costs	**Enabler-6-**Technical effectiveness of blockchain (operational efficiencies,smart contract,automation)	**Enabler-7-** The existence of improved new regulations and incentives	**Enabler-8-** Exercising and educating stakeholders (designers, building owners)	**Enabler-9-** Decentralization and disintermediation
Barrier-A-Political/Governmental challenges (Uncertain/insufficient regulations, Lack of know-how, proper vision of policy decision makers)									
Barrier-B-Economic and social challenges (Market dynamics, sustainability vs profit paradox, lack of suitable business models,Lack of CE/BCT understanding and perception, difficulty of changing settled habits ideas/cultures)									
Barrier-C-Technological challenges (blockchain technological feasibility/immaturity/ uncertainty problems, lack of technological know-how, existing old infrastructure-related barriers, blockchain storage capacity)									
Barrier-D-Data related challenges (possible inefficiencies in providing data [immutability/security/privacy/confidentiality/availability], traceability and transparency related issues [difficulties in determination of appropriate level of data transparency], data ownership and liability)									
Barrier-E-Blockchain performance challenges (Resilience against combined attacks is a challenge for BCT, complexity of blockchain, Lack of scalability of BCT, trade-off between scalability/ decentralization/ and security, high latency of BCT)									
Barrier-F-BIM and blockchain integration challenges (difficulty in tracking changes in BIM, lack of storage and scalability, legal uncertainty)									
Barrier-G-Environmental/ Ecological challenges (Energy consumption of BCT, Lack of biodegradable resources in circular supplies, Lack of validity with respect to the ecological benefits of product recovery)									
Barrier-H-Ownership and liabilities-related challenges (Lack of clarity on roles and responsibilities in BC/CE enabled system, Intellectual Property (IP) and know-how access issues in a more transparent environment)									
Barrier-I-Organizational challenges (Inertia in business to change, Lack of organizational and business model readiness, the paradox of simultaneous competition and cooperation)									

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

9.

* 14. Do the enablers address the challenges for transitioning into a blockchain supported circular economy? At what level ? Please select from 1 to 5. (1 represents the very low level and 5 represents very high level)

0 3 5

* 15. At what level/how well do you think blockchain can support the circular economy? Please select from 1 to 5. (1 represents the very low level and 5 represents very high level)

0 3 5

16. What are your suggestions to remove barriers to blockchain and circular economy usage in the construction industry?

EXAMINING BARRIERS-ENABLERS OF BLOCKCHAIN AND CIRCULAR ECONOMY USAGE IN THE CONSTRUCTION INDUSTRY

10.

THANK YOU FOR YOUR VALUABLE TIME, PARTICIPATION AND CONTRIBUTION
BEST REGARDS,