ENHANCING CIRCULAR ECONOMY ADOPTION IN THE INDUSTRIAL STEEL CONSTRUCTION INDUSTRY: A BLOCKCHAIN-BASED INFORMATION FLOW FRAMEWORK

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ABSTRACT

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The circular economy (CE) is an economic model that focuses on reducing waste and maximizing the efficient use of resources. It aims to extend the life cycle of products and materials by promoting recycling, reuse, and other strategies. For many sectors, the transition to CE is critical to achieving long-term sustainability goals. However, literature reviews and semi-structured interviews revealed that the level of CE adoption and transition in the construction industry is quite limited, and barriers have been identified in this context. In this thesis, a conceptual blockchain-based information flow framework is developed to increase CE adoption in the construction industry and address the identified barriers. With the help of blockchain technology, the proposed framework can record, store, and distribute data that is part of the processes to the participants. It is aimed to have an effective flow of information between all participants throughout the life cycle of construction materials. Thus, CE awareness of the whole ecosystem can be increased through the involvement of stakeholders using this framework. Furthermore, increased circularity will increase sustainability by reducing the negative environmental impacts of construction processes. Moreover, the implementation of this framework is planned to utilize emerging technologies such as the Internet of Things (IoT) and Radio Frequency Identification (RFID) for data collection. An example application of the proposed framework is presented for industrial steel construction and tested through a case study. The case study was carried out in a large Engineering, Procurement, and Construction (EPC) company operating in the field of industrial steel construction, and evaluations were obtained from experts working in this company. Thus, based on the findings of this study, it is concluded that the presented framework can contribute to CE transition and CE adaptation.

Keywords: Circular Economy, Adaptation, Sustainability, Blockchain

ÖZ

ENDÜSTRİYEL ÇELİK İNŞAAT SEKTÖRÜNDE DÖNGÜSEL EKONOMİYİ GELİŞTİRMEK: BLOKZİNCİR TABANLI BİLGİ AKIŞ ÇERÇEVESİ

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Döngüsel ekonomi (CE), atıkları azaltmaya ve kaynakların verimli kullanımını en üst düzeye çıkarmaya odaklanan ekonomik bir modeldir. Geri dönüşüm, yeniden kullanım ve diğer stratejileri teşvik ederek ürün ve malzemelerin yaşam döngüsünü uzatmayı amaçlar. Birçok sektör için CE'ye geçiş, uzun vadeli sürdürülebilirlik hedeflerine ulaşmak için kritik önem taşımaktadır. Ancak literatür taramaları ve yarı yapılandırılmış görüşmeler, inşaat sektöründe CE'nin benimsenme ve geçiş düzeyinin oldukça sınırlı olduğunu ortaya koymuş ve bu bağlamda engeller tespit etmiştir. Bu tezde, inşaat sektöründe CE'nin benimsenmesini artırmak ve belirlenen engelleri ele almak için konseptsel blok zinciri tabanlı bir bilgi akışı çerçevesi geliştirilmiştir. Blok zinciri teknolojisinin yardımıyla, önerilen çerçeve süreçlerin bir parçası olan verileri kaydedebilir, saklayabilir ve katılımcılara dağıtabilir. İnşaat malzemelerinin yaşam döngüsü boyunca tüm katılımcılar arasında etkili bir bilgi akışı olması hedeflenmektedir. Böylece, bu çerçeveyi kullanan paydaşların katılımıyla tüm ekosistemin CE farkındalığı artırılabilir. Ayrıca döngüselliğin artması, inşaat süreçlerinin olumsuz çevresel etkilerini azaltarak sürdürülebilirliği artıracaktır. Ayrıca, bu çerçevenin uygulanmasında veri toplama için Nesnelerin İnterneti (IoT) ve Radyo Frekansı ile Tanımlama (RFID) gibi gelişmekte olan teknolojilerin kullanılması planlanmaktadır. Önerilen çerçevenin örnek bir uygulaması endüstriyel çelik konstrüksiyon için sunulmuş ve bir vaka çalışması ile test edilmiştir. Vaka çalışması, endüstriyel çelik konstrüksiyon alanında faaliyet gösteren büyük bir Mühendislik, Tedarik ve İnşaat (EPC) şirketinde gerçekleştirilmiştir ve bu şirkette çalışan uzmanların değerlendirmeleri alınmıştır. Dolayısıyla, bu çalışmanın bulgularına dayanarak, sunulan çerçevenin CE geçişine ve CE adaptasyonuna katkıda bulunabileceği sonucuna varılmıştır.

Anahtar Kelimeler: Döngüsel Ekonomi, Adaptasyon, Sürdürülebilirlik, Blok zincir

To my family

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AI: Artificial Intelligence

AR: Adaptive Reuse

BFT: Byzantine Fault Tolerance

BIM: Building Information Modeling

CDW: Construction Demolition Waste

CE: Circular Economy

DACs: Decentralized Autonomous Corporations

DAOs: Decentralized Autonomous Organizations

De: Deconstruction

Dapps: Decentralized Applications

DL: Distributed Ledger Technology

DPoS: Delegated Proof of Stake

EU: European Union

FAT: Factory Acceptance Test

IoT: Internet of Things

LCA: Life Cycle Assessment

PBFT: Practical Byzantine Fault Tolerance

PoS: Proof of Stake

PoW: Proof of Work

P2P: Peer-to-Peer Network

RFID: Radio Frequency Identification

RL: Reverse Logistics

TPS: Transactions per Second

WLC: Whole Life Costing

3Rs: Reduce, Reuse, Recycle

CHAPTER 1

INTRODUCTION

The construction industry has played a significant role in economic growth, but its environmental and social impacts have become concerning in recent years (Illankoon & Vithanage, 2023). According to the evidence presented, the industrial sector utilizes approximately half of the Earth's mineral resources. It is responsible for producing as much as 35% of the waste deposited in landfills (Baek et al., 2013). Also, as per the findings of the United Nations Environment Programme in 2021, the building and construction industry accounts for 36% of total global final energy consumption and contributes to 37% of energy-related carbon dioxide (CO_2) emissions worldwide (Hamilton, 2021). Nevertheless, the construction industry traditionally follows a linear economic model in which materials are extracted, used, and then disposed of. This model is characterized by a high degree of waste and inefficiency. The industry consumes a significant amount of Earth's resources, and many of them are wasted before they can reach their full potential (Oluleye et al., 2022). Eurostat's (2023) report states that while waste generation has decreased, the European Union (EU) is not progressing as expected towards achieving its target for circular material use in the construction industry.

The circular economy (CE), which is defined as an economic model that aims to optimize resource usage and reduce waste generation, offers a crucial solution for the construction sector. CE is a viable strategy to prevent the negative economic, social, and environmental impacts of the linear economy (Kedir et al., 2023). Therefore, it requires a significant change in adopting this economic model to reduce resource depletion and promote sustainable practices. Despite the proven effectiveness of the CE for the construction industry, its adoption and implementation have remained at a low level due to the presence of specific barriers. The construction industry faces interconnected technical, organizational, and market barriers, including an underdeveloped market for professional actors, a need for more information about used construction products, and an inadequate regulatory framework for incorporating recycled materials into new structures (Sigrid Nordby, 2019).

This thesis aims to develop a blockchain-based information flow framework to address the barriers to CE adaptation observed as a result of the conducted studies. In addition, the framework intends to create a CE awareness among all stakeholders of the construction process. The framework was tested through a small-scale case study that was designed as face validation conducted in a large Engineering, Procurement, and Construction (EPC) company. The results of the case study show that the framework can provide a solution to CE barriers and increase CE culture in the construction industry. It contributes to the monitoring of energy consumption and CO_2 emissions, traceability of material information, waste and scrap management, standardization, and increased cooperation between stakeholders in the construction sector.

To this end, the thesis is divided into five main chapters. First, a comprehensive literature review is conducted. This literature review includes an understanding of the CE concept, existing CE barriers and possible solutions in the construction industry, the basics of blockchain and its place in the construction industry, and studies using blockchain technology to improve CE. Chapter 3 describes the methodology used in this study, including the literature review on the focused barriers, interviews with experts, assessment of CE barriers, the structure of the developed framework, and the case study. Chapter 4 describes the findings from the literature review and semi-structured interviews with experts. It also highlights the barriers focused on in this study.

Chapter 5 outlines the characteristics of the developed framework and its application in industrial steel construction and validation. In addition, it discusses the contributions and challenges of the proposed framework. The final chapter summarizes the overall study. It also presents the limitations of this thesis and recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

Chapter 2 covers the concepts of CE and blockchain technology and explores their application areas in the construction industry. It also explains the challenges and enablers associated with CE adoption and presents the basics of blockchain technology.

2.1 Circular Economy

2.1.1 The Concept of Circular Economy

The history of the CE concept dates back many years, and it is difficult to trace it back to a specific date or author. However, many scholars believe Boulding (1966) forms a basis for this concept in his work, The Economics of the Coming Spaceship Earth (Wautelet, 2018). He argued that establishing circular systems within the world economy is essential to ensure the long-term survival of human life on Earth by drawing an analogy of a closed system like a spaceship. This was followed by Pearce & Turner (1989), who built on the ideas of Boulding to explain the shift from the traditional linear economy to the CE (Wautelet, 2018). Much work and development has taken place in the academic and practitioner communities since then. In 2021, more than 13,000 papers were published on CE, approximately 60% in 2020 or 2021. This increase in research interest is likely due to the growing recognition of the importance of CE. In addition to the growth in research interest in CE, there has also been a significant increase in policy efforts and private sector initiatives in support of CE (Hartley et al., 2020). For instance, the European Union has initiated large-scale CE policy efforts, and many large corporations and startup companies are exploring CE approaches (Brown et al., 2021).

Many CE definitions have been made and accepted in the past in industry and academia. The Ricoh Group introduced the Comet Circle concept in 1994 as a way to contribute to the development of CE. As depicted in Figure 1, the Comet Circle is a comprehensive framework for reducing environmental impact throughout the entire lifecycle of materials, from manufacturing to end-of-life. It is founded on the belief that all product parts should be designed and made to be recyclable or reusable. This concept is divided into two main loops. The inner loop and the outer loop. The inner loop represents the reuse and recycling of products and parts. The outer loop represents the recovery and recycling of materials. They aim to maximize the amount of materials that are reused or recycled and to minimize the amount of materials that are sent to landfills (Ricoh Group, 1994).

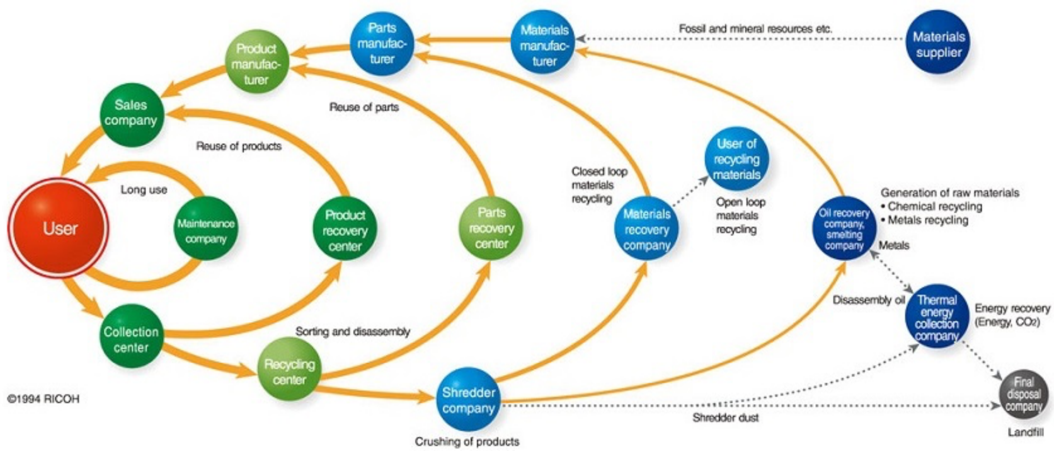

Figure 1. Comet Circle Concept for Circular Economy (Ricoh Group)

In addition, The Ellen MacArthur Foundation offers one of the most widely accepted definitions of CE. They define it as a system that is restorative and regenerative by design. This means that it aims to keep products, components, and materials at their highest utility and value at all times. Also, The concept of a CE is frequently described as a system that focuses on minimizing the use of resources and the generation of waste, emissions, and energy loss (EMF, 2015). This is accomplished by promoting actions such as designing products for durability, practicing maintenance, repairing items, reusing materials, remanufacturing products, refurbishing goods, and recycling components (Geissdoerfer et al., 2017). Also, they introduced the butterfly diagram. The butterfly diagram in Figure 2 visually represents the CE system. It shows how materials are kept in circulation in a sustainable way. The diagram has two main cycles: the technical cycle and the biological cycle. The technical cycle focuses on keeping products and materials in use for as long as possible. This can be done through practices such as reuse, repair, remanufacture, and recycling. On the other hand, the biological cycle focuses on returning nutrients from biodegradable materials to the Earth. This helps to regenerate the natural environment. The butterfly diagram is a helpful tool for understanding the CE and how it can be used to reduce waste and protect the environment.

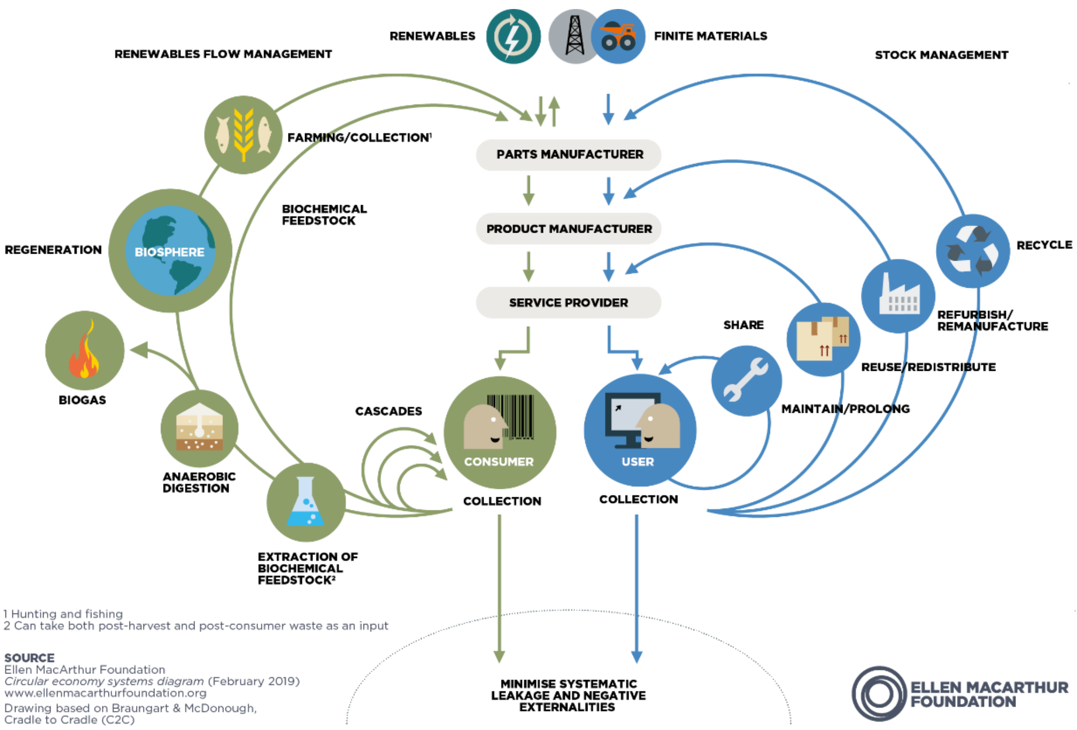

Figure 2. Butterfly Diagram (EMF, 2015)

On the other hand, the most important problem for sustainable development is the linear (one-way) input flow of materials and energy between nature and the human economy. Korhonen et al., (2018) have taken a critical scientific approach to the emerging business concept of the CE. As shown in Figure 3, they argue that a successful CE will contribute to all three dimensions of sustainable development: economic, environmental, and social. The proposed approach describes a CE as a system within society's production-consumption processes that optimizes the value derived from the linear flow of materials and energy between nature and the human economy. This optimization is achieved by implementing cyclic material flows, renewable energy sources, and cascading energy usage. They claim that a successful CE aligns with all three dimensions of sustainable development (Korhonen et al., 2018).

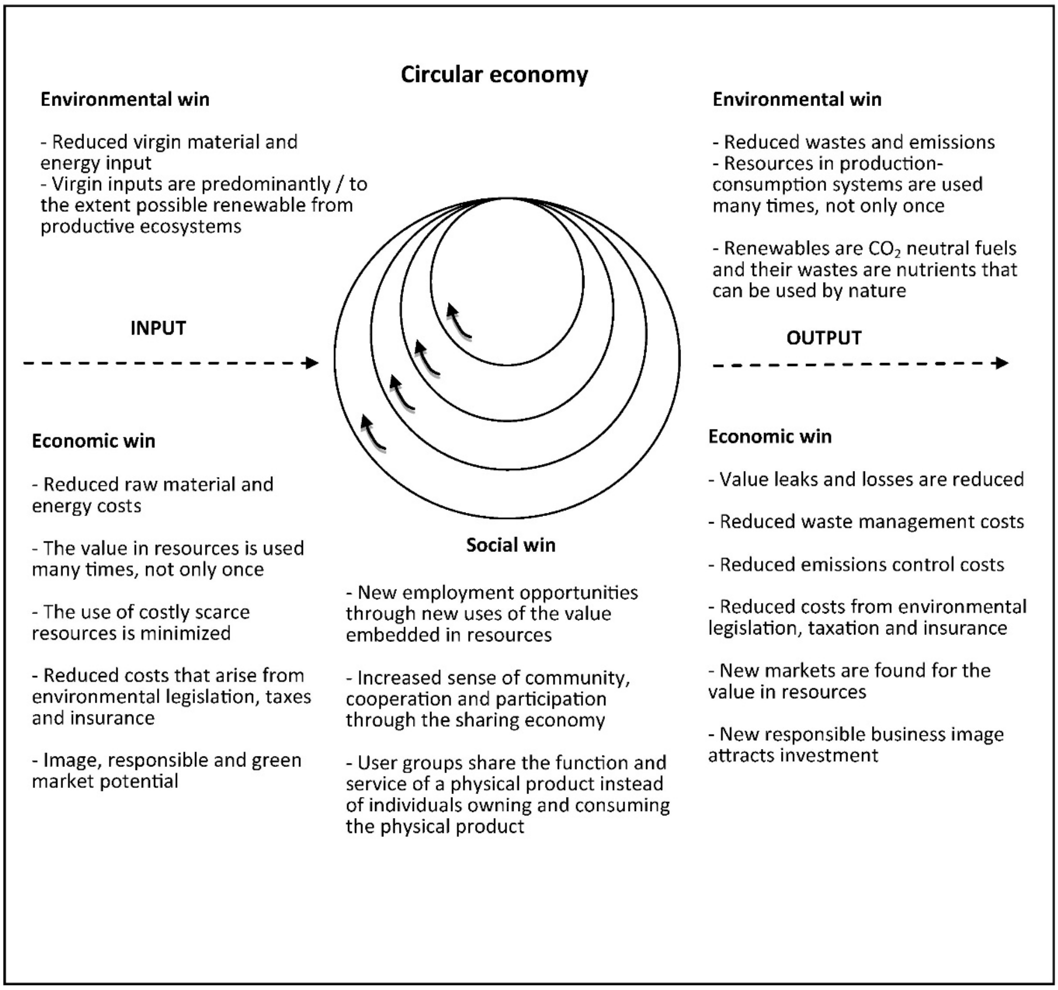

Figure 3. A Diagram for Circular Economy (Korhonen et al., 2018)

Furthermore, the Ellen MacArthur Foundation states that more recent theories have helped to refine and develop the concept of CE, which has an extensive definition. CE is a system that aims at the elimination of waste and pollution, the circulation of products and materials at their highest value, and the regeneration of natural systems. Some of the more recent theories that have contributed to the development of CE like performance economy, closed supply chains, cradle-to-cradle, 3Rs, and blue economy (EMF, 2015). All of these theories share a common goal of sustainable development, but they also offer different perspectives on how this goal can be achieved. Brief explanations of the theories that have contributed to the development of the CE follow; performance economy focuses on designing products and services that are as efficient as possible, so that they require less resources and energy to produce and use; cradle to cradle is a design philosophy that seeks to create products that can be reused or recycled infinitely, without the need to extract new resources; closed supply chains aim to eliminate waste by ensuring that all materials and components are reused or recycled at the end of their life; The 3Rs (reduce, reuse, recycle) are a set of principles that can be used to reduce waste and pollution; blue economy is an approach to economic development that focuses on the sustainable use of marine resources.

Kirchherr et al., (2023) have done one of the most comprehensive studies on the definitions of the CE. In this systematic analysis, 221 definitions were examined. As a result of this analysis, they found that the CE concept has evolved over the past five years, with consolidation and differentiation in definitions, and academics are increasingly calling for a fundamental systemic change to enable the circular economy, especially in supply chains. Moreover, sustainable development is generally accepted as the primary objective of the CE, but there is debate about whether it can mutually support environmental sustainability and economic development. The recent transition to the CE is based on a broad alliance of stakeholders, including manufacturers, consumers, policymakers, and academics. Indeed, the CE concept is still evolving, but there is a growing consensus that it requires a fundamental shift in the way we produce and consume goods and services. The CE is seen as a way to achieve sustainable development, but there is debate about whether it can also support economic growth. The transition to CE will require the cooperation of a wide range of stakeholders, including businesses, governments, and consumers (Kirchherr et al., 2023).

However, there is still not widely accepted and precise definition of a CE; instead, the concept is applied in different ways by stakeholders depending on their specific interests (EMF, 2015).

The authors of the CGR report used the ‘Monitoring Framework for Economy-wide Material Loop Closing to measure global circularity’ (CGR, 2023). This framework was developed by Mayer et al., (2019) and uses official statistics on resource extraction, consumption, and waste flows to create a mass-balanced assessment. Despite the accelerated increase of studies, the CGR report reveals that global circularization remains notably low in 2023. Although the accelerated increase of studies, the CGR report reveals that global circularization remains notably low in 2023. The first edition of our Report in 2018 was the first ever to measure global circularity, as shown in Figure 4, finding it was 9.1%. It dropped to 8.6% in 2020 and has now fallen to 7.2% (CGR, 2023).

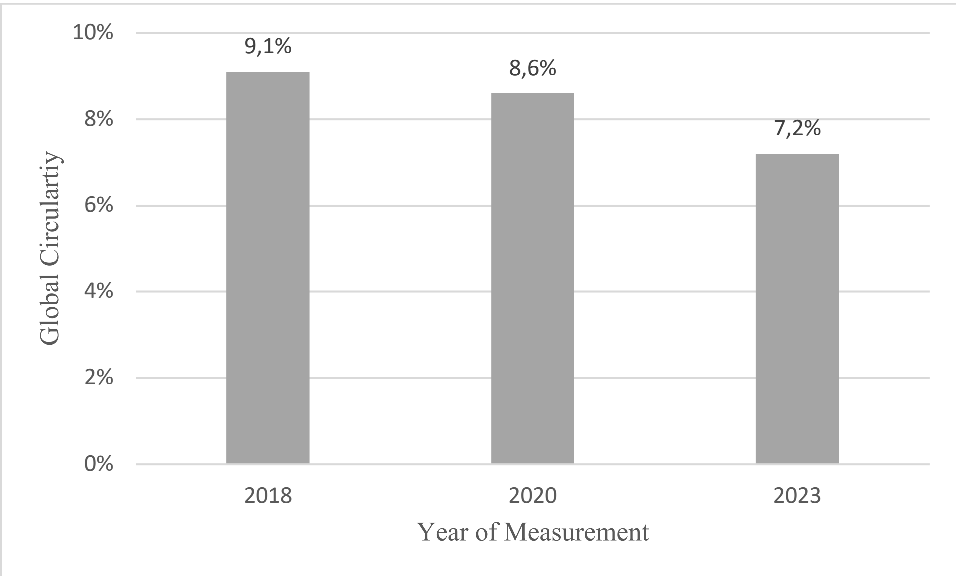

Figure 4. Global Circularity Rates

2.1.2 Why the Circular Economy Is Needed?

The global population is expected to reach almost 10 billion by 2050, and this will put a strain on the Earth's resources with various problems (WPP, 2019). Environmental issues are threatening the planet's ecological balance. These problems include biodiversity loss, pollution, resource depletion, and excessive land use (Geissdoerfer et al., 2017). It will also bring severe social and economic problems. People's expectations for a good life are unmet because of issues like not having a job, working in bad conditions, being poor, and not having enough money to live on (A. V Banerjee & Duflo, 2011). Economic challenges can lead to financial and economic instability for businesses and economies. These challenges include uncertain supply chains, complicated ownership arrangements, lack of market regulations, and incentives that may not align with sustainable and stable economic growth. As a result, businesses and economies are more vulnerable to crises and disruptions (Geissdoerfer et al., 2017). Therefore, it is clear that the current linear economic model, which is based on the extraction, production, consumption, and disposal of resources, is not sustainable. This is because it leads to the depletion of resources and the accumulation of waste. Urgent efforts are needed to address these challenges and protect the Earth's natural systems. Therefore, the CE concept has become a leading approach to sustainable development because it supports the use of closed-loop systems for materials and resources (Shojaei et al., 2021a). Flowcharts representing linear economy and circular economy are shown in Figure 5.

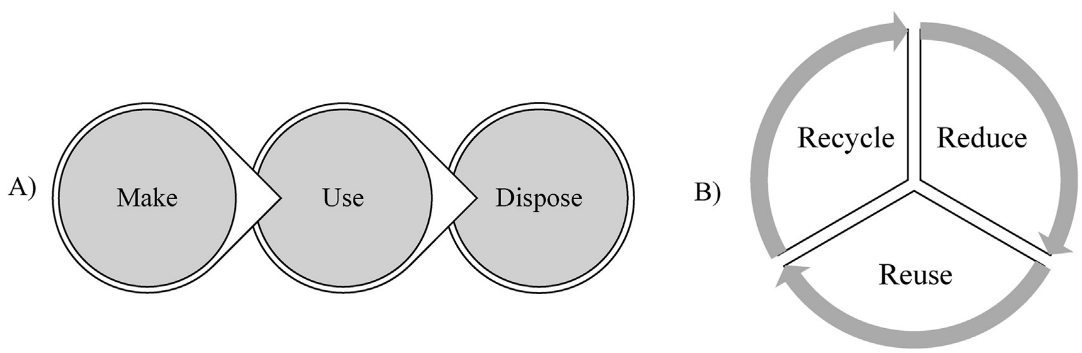

Figure 5. A) Linear Economy; B) Circular Economy

Therefore, awareness of these problems has increased in recent years, with a growing interest in CE to solve these problems among practitioners and academics (Kirchherr et al., 2017). They have actively written about or developed concepts and potential advantages (Beaulieu et al., 2016; Kirchherr et al., 2023).

2.1.3 The Circular Economy in the Construction Industry

Construction organizations need to find ways to make construction more sustainable by reducing the number of resources used as the amount of energy consumed, and the amount of greenhouse gas emissions produced.

In the EU, construction and demolition activities account for around 25-30% of the total waste generated. Moreover, the production of cement and steel, primarily intended for construction purposes, is accountable for almost 10% of global carbon dioxide emissions (EMF & Arup, 2022).

CE is a promising approach for construction organizations and policymakers because it can help to reduce waste and pollution by keeping materials in use for as long as possible (Illankoon & Vithanage, 2023).

Due to the substantial depletion of resources, inefficiency, and environmental impact linked to the construction sector, the transition towards the CE approach has emerged as a primary objective (Charef et al., 2021a). Figure 6 shows that the majority of articles on CE in the construction industry were published in the last four years. Notably, in recent years, it has been seen that there has been a significant interest in this topic in the construction industry (Charef et al., 2021a).

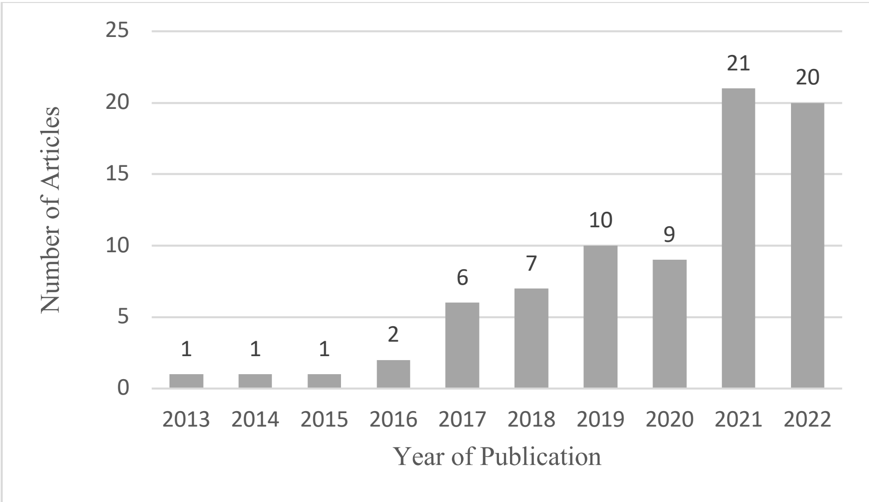

Figure 6. Circular Economy in Construction Industry Publications by Year (Charef et al., 2021a)

However, due to its well-known reluctance to embrace change, complex product structures, and status as one of the industries that have adopted digital technologies the least globally, the construction sector faces exceptional challenges in effectively adopting CE principles (Wuni, 2022a).

2.1.3.1 Enablers & Barriers of Circular Economy in the Construction Industry

There has been extensive research on the enablers and barriers to CE within the construction industry. Numerous scholars have dedicated their attention to this subject, and this section will outline many of their findings and recommendations for future research.

The study results indicate that there are four nested categories of barriers: cultural, regulatory, market, and technological. Hart et al., (2019) have grouped the enablers and barriers to circularity in the construction industry into financial, sectoral, cultural, and regulatory. Then, Guldmann & Huulgaard, (2020) categorize the factors that influence the adoption of CE practices in the construction industry into four primary groups: market and institutional barriers, value chain barriers, organizational barriers, and employee level barriers. Forty-seven expert interviews and a survey of 208 respondents were conducted to identify barriers to the circular economy in the EU by Kirchherr et al., (2018a). By reviewing the CE in the context of the construction industry, Charef et al. (2021b) also classified common barriers into six different categories: organizational, economic, technical, social, and environmental. In addition, Ababio & Lu (2022) performed an analysis of articles filtered on CE implementation barriers and enablers in construction. The researchers found that although the barriers and drivers at each level may differ, the critical system levels of CE implementation (micro, meso, and macro) are interrelated. They categorized the critical barriers to implementing CE-oriented strategies into five main themes: definitional and theoretical misconceptions, political and legislative, social and cultural, financial and economic, and technological barriers. A summary of the work done is presented in Figure 7, considering that the successful implementation of CE depends on the contributions of stakeholders and the implementation of appropriate facilitation strategies.

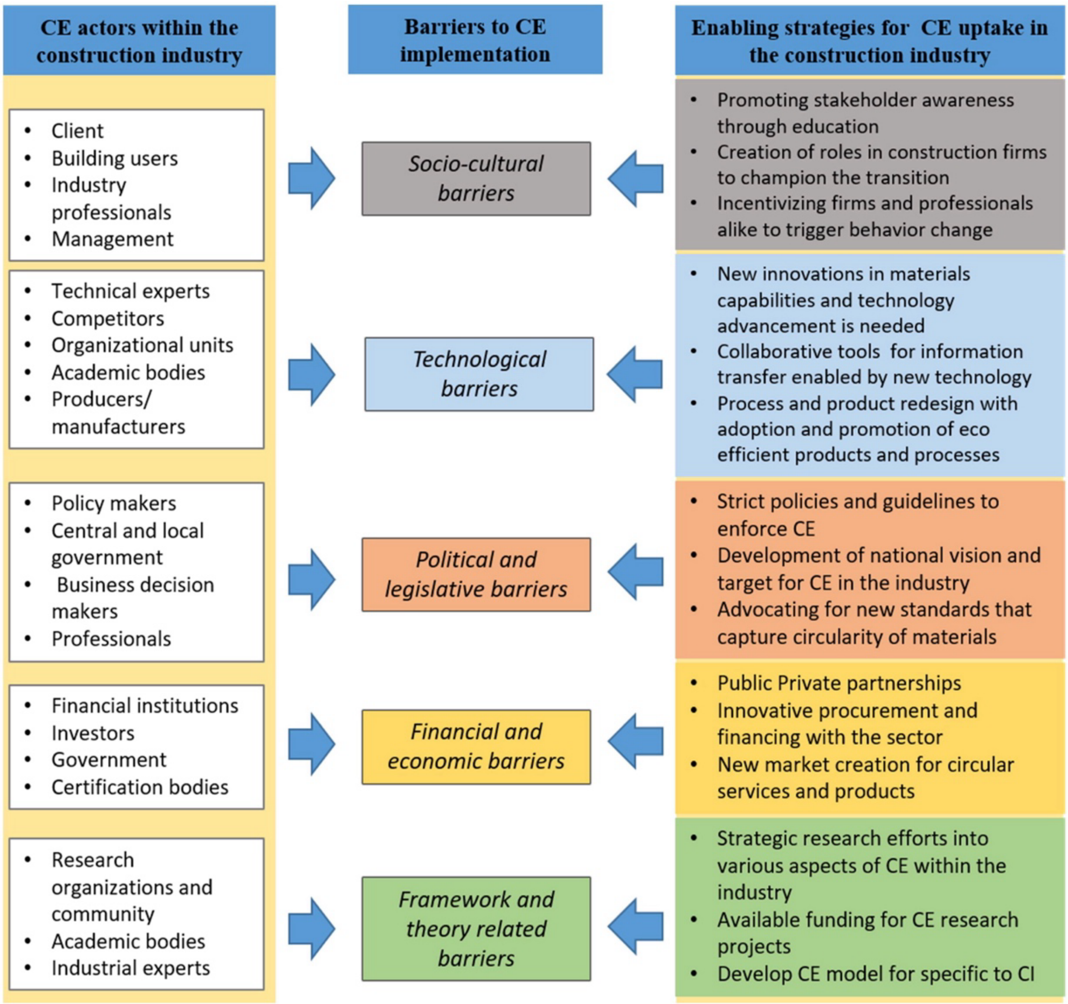

Figure 7. Circular Economy Implementation Framework for the Construction Industry
(B. K. Ababio & Lu, 2023)

Furthermore, Adams et al., (2017) have tried to analyze current challenges and enablers for CE in the construction industry in 2017. To this end, they conducted a survey with researchers and practitioners and an event in which 97 attendees, including a wide range of construction stakeholders, discussed the challenges and enablers in the adaptation of CE. The survey results, graphically depicted in Figure 8 and Figure 9, are shown below.

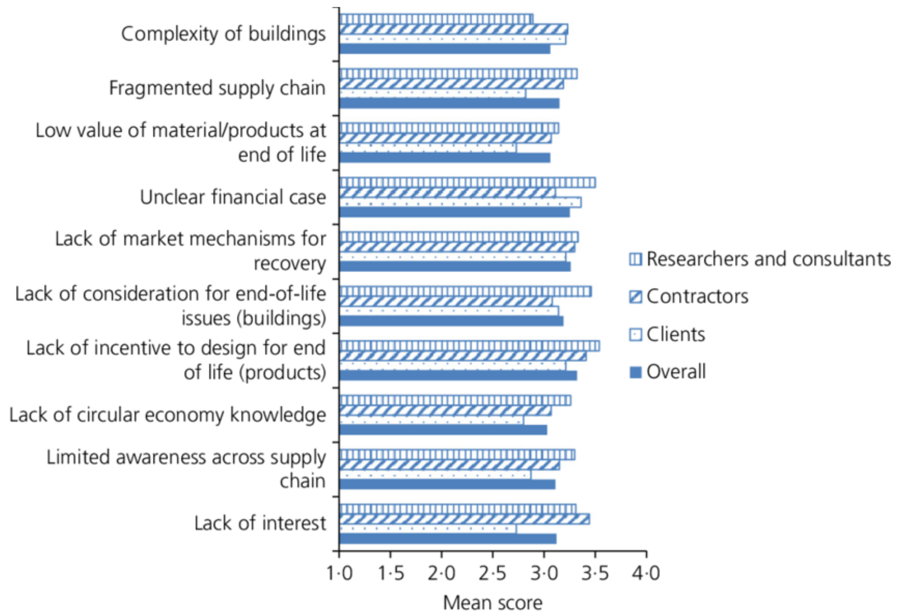

Figure 8. The Top Challenges for the Adoption of Circular Economy Across the Construction Industry (Adams et al., 2017)

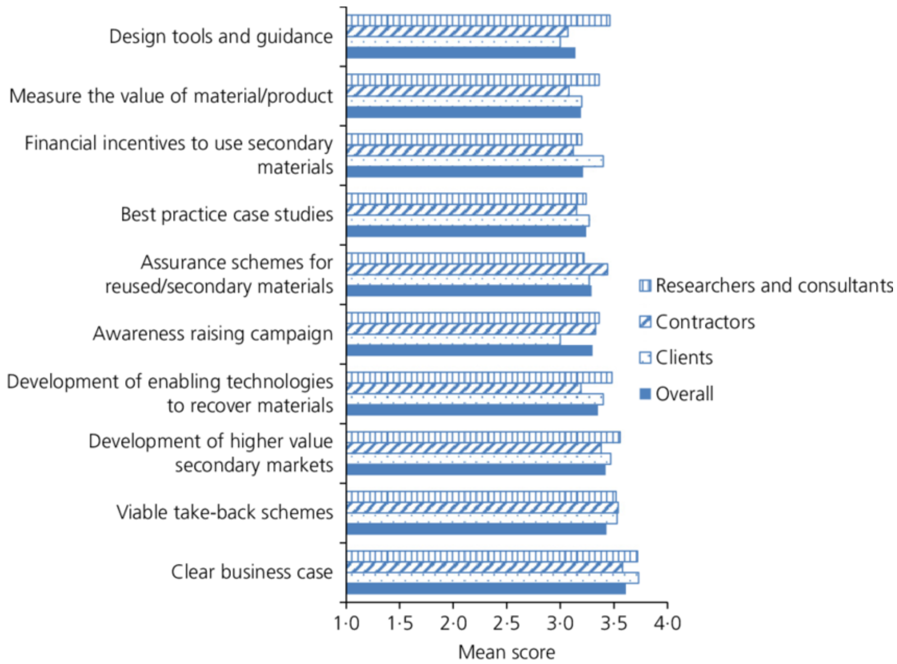

Figure 9. Top Enablers for Adoption of Circular Economy Across the Construction Industry (Adams et al., 2017)

According to recent research, there are significant obstacles to the implementation of CE principles in the construction industry. One of the main challenges is the lack of efficient information flow, which can lead to delays, misunderstandings, and mistakes in the decision-making process. To address this issue, researchers recommend the use of a guidance tool that provides clear and accessible information, helping stakeholders make informed choices and facilitating the transition to a more sustainable and circular model of construction.

2.1.3.1.1 Enablers of the Circular Economy in the Construction Industry

CE enablers are emerging as key drivers of sustainable change as the construction industry faces challenges such as resource depletion and environmental impact. This includes innovative technologies, supportive policies & and regulations, economic drivers, and collaborative approaches. A comprehensive exploration of the key enablers driving the construction industry toward a more circular and sustainable future is presented in this section.

2.1.3.1.1.1 Holistic Approach of Circular Economy

One weakness of the construction industry is its compartmentalized approach, where project phases and stakeholders are separated, resulting in inadequate communication. In the context of the CE, it is critical to adopt a more holistic approach that involves all stakeholders and all asset phases, as outlined by the established framework (Charef & Lu, 2021). There is a need for a holistic approach within the construction industry to what a CE means for them. For materials, processes, and systems to be circular, researchers need to work together to better understand the principles and practices of CE. B. Ababio & Lu, (2022) emphasize that leadership and collaboration are key to making CE work in practice. To this end, developing a roadmap applicable to all levels of the economy and facilitating a smooth transition is crucial. The study of CE projects by Rizos et al., (2016) also found that a strong culture of environmental leadership was the most important factor in the success of CE projects. In addition, Bao et al., (2019) suggest that the construction industry should rethink its circular economic philosophy and clarify its practical scope so that the industry can sustain its prosperity over the long run.

2.1.3.1.1.2 Technology and Innovation

The implementation of CE practices in the construction industry is enhanced by emerging technologies and innovative practices. There are several examples in the literature where CE and emerging technologies are applied together. B. K. Ababio & Lu, (2023) assert that a thorough redesign of processes, systems, and products is crucial for transitioning to the CE. Yet, they emphasize that these significant changes necessitate the support of appropriate technologies and strategies. Emerging technologies such as blockchain, BIM, digital twin, sensors, and controls, and IoT can be investigated for their potential benefits in CE. Furthermore, sharing platforms for underutilized assets can be developed and resource recovery technologies enhanced (Hopkinson et al., 2018). Kirchherr et al., (2018b) also note that innovation in materials and process development is critical with the trend toward cleaner production and reducing waste at the source.

2.1.3.1.1.3 Supportive Policies and Regulations

Policy support plays an important role as a key enabler for the transition to CE. It provides guidance for innovation, establishes metrics and influences practices (B. K. Ababio & Lu, 2023). Bao & Lu, (2020) pointed out that in addition to maintaining supportive policies, companies should be educated to adopt the circular economy as a fundamental business principle. This approach aims to create a CE approach throughout the construction industry and promote long-term prosperity. Another key enabler identified was regulatory reform. Robust regulatory reforms that promote collaboration along the value chain are urgently needed to achieve the goals outlined in the CE (Hill, 2015). Moreover, according to Adams et al., (2017) findings, green public procurement requirements were seen as an important enabler, especially by designers, researchers, and consultants.

2.1.3.1.1.4 Economic Benefits

There are economic benefits in the construction industry that will facilitate the transition to CE. Shifting the focus to the long-term value of physical assets can be accomplished through approaches such as Whole Life Costing (WLC) and new assessment methodologies that incorporate environmental, social, and governance factors. WLC has long been advocated as a potential enabler for energy efficiency initiatives (Hart et al., 2019). B. Ababio & Lu, (2022) mentioned the long-term investment that can be made to WLC to support the CE business case in the construction sector. Additionally, cost-saving inputs act as another enabler. Hart et al., (2019) provided examples, highlighting how using recycled materials can lead to financial savings while designing for disassembly also facilitates quicker assembly.

2.1.3.1.2 Barriers to the Circular Economy in the Construction Industry

The construction industry faces significant obstacles in adopting CE principles as it moves towards a more sustainable future. Technological challenges, regulatory inconsistencies, economic constraints, and collaborative barriers collectively slow progress. This section offers a brief overview of the main obstacles that hinder the construction industry's progress towards circularity and sustainability.

2.1.3.1.2.1 Economic Barriers

Economic barriers in CE have been emphasized and identified as a significant challenge in the literature and research. Adams et al., (2017) and Kirchherr et al., (2018b) assert that the low cost and easy availability of raw materials make them more attractive than recycled products. Therefore, more raw materials are used, and recycling percentages decrease. Moreover, inadequate private and public financial support is another economic barrier (Kirchherr et al., 2018b). Although businesses require financial support, they do not obtain sufficient financial support and do not take the necessary steps to transition to the CE. Sauvé et al., (2016) note that products with longer service lives have higher upfront investment costs. As expected, companies give up making these investments if the benefit is equal to or lower than the cost. Additionally, Kissling et al., (2013) mentioned that the CE encounters obstacles from the significant expenses linked with recovering products, as well as the significant labor costs associated with dismantling products and separating waste at the source.

2.1.3.1.2.2 Social and Cultural Barriers

The social and cultural barriers to CE in the construction industry mainly result from the industry's conventional linear production approach, limited awareness, and lack of collaboration between different stakeholders (Hart et al., 2019). Lack of awareness and willingness for CE is one of the most common barriers. Many studies demonstrate that awareness of CE in the construction industry is low due to construction companies' culture and social reasons (Kirchherr et al., 2018b). Construction companies' culture is committed to preserving the existing linear system and is far from the approach of long-term thinking. Construction firms often face difficulties in implementing CE due to ineffective collaboration and partnerships with others. This situation arises when different departments within the same company do not communicate or share information. CE practices include product design for recycling and remanufacturing (Hart et al., 2019).

2.1.3.1.2.3 Regulatory and Policy Barriers

The lack of a regulatory framework for the CE presents a significant barrier to its adoption in academic research. This encompasses a lack of global consensus on how to promote the CE through policy, as well as a lack of ambitious targets beyond basic landfill diversion (Hartley et al., 2020).

The absence of clear regulations defining the "end of waste" is the biggest legislative and policy barrier to the CE (Adams et al., 2017). Many authors cite laws and regulations as obstacles, usually related to the handling and categorizing of waste (B. Ababio & Lu, 2022; Hart et al., 2019; Kirchherr et al., 2018b). There is an increasing awareness among governments that laws and regulations need to be reformed to promote the CE. Nevertheless, further effort is needed to facilitate businesses' adoption of circular practices more conveniently and efficiently. Governments play a major role in making the CE transition. They can support the transition to the CE by providing financial and legal incentives to businesses; however, these incentives seem to be lacking (Acharya et al., 2018).

2.1.3.1.2.4 Technological Barriers

Technological barriers present significant challenges to implementing the CE, hindering the widespread adoption of circular practices and limiting the potential environmental and economic benefits. These obstacles arise from several factors, including the requirement for innovative technologies and the challenges of developing and implementing sustainable technologies. Häkkinen & Belloni, (2011) identified a significant challenge in the construction of sustainable buildings as the lack of a standardized approach to integrating the various aspects and steps of sustainable practices into the actual construction process. Additionally, challenges exist in the area of CE due to difficulties in data collection and storage, such as incorrect collection, low-quality data, and incompatible formats. Companies also encounter barriers due to the lack of standards and protocols in areas such as product development and data sharing (Trevisan et al., 2023). Further, the inherent complexities of the construction process, such as lack of transparency, oversight, and coordination, are often seen as additional technological barriers, according to Torgautov et al.(2021). Lastly, Wuni, (2022b) identified a shortage of technologies that support efficient and organized collection, separation, recovery, recycling, and reuse of waste in the construction sector as a barrier.

2.1.3.1.2.5 Environmental Barriers

Environmental barriers predominantly occur during the end-of-life stage of the asset, specifically within the management of construction and demolition waste (CDW) and selective demolition processes. In situations involving deconstruction (De), reverse logistics (RL), and adaptive reuse (AR), storage space emerges as a concern, according to Chileshe et al., (2015).

The transition to circular models in the construction sector is still at an early stage of development, and the collaboration of governments and all stakeholders involved in construction processes will play an important role (Illankoon & Vithanage, 2023). In order to overcome all these barriers, radical changes should be made in the construction industry, technologies that enable the adoption of CE should be developed, and regulations & incentives should be made.

2.2 Blockchain Technology

Blockchain is a distributed ledger technology (DLT) that enables secure, transparent, and tamper-proof record-keeping (Das et al., 2022). It is a decentralized system, which means it is not controlled by any single entity. Instead, it is maintained by a network of computers, each holding a copy of the ledger. It can be defined as a distributed database (the ledger) that operates in a shared and synchronized environment (the chain) in which users can verify the information

(Aste et al., 2017) (Figure 10). This makes it extremely challenging to tamper with the data, as any modifications would have to be made to all copies of the ledger.

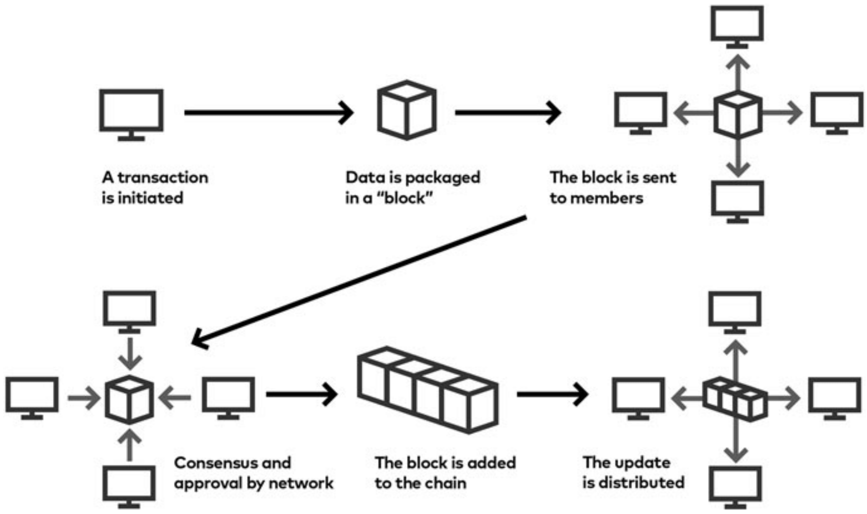

Figure 10. Blockchain Mechanism

2.2.1 Blockchain Technology Fundamentals

In this section, the basic features of blockchain are mentioned. The notable features that make blockchain technology appealing include its role as a distributed ledger, decentralized control, transparency, permanence of transactions, resilient structure preventing tampering or manipulation, and open accessibility (Xu et al., 2019).

2.2.1.1 Decentralization

Centralized systems are vulnerable to a single point of failure, meaning that if that central point goes down, the entire system will fail. Conversely, blockchain systems adopt a decentralized approach, eliminating the possibility of a single point of failure. Instead, data is shared and updated across a network of computers, making it more resilient, secure, and scalable (El Bassam, 2021). Each node in the network participates in replicating all or part of blocks, collectively authenticating data security. Members are identified by unique addresses within the network (Arashpour et al., 2019).

2.2.1.2 Immutability

Blockchain is a system that records transactions in a tamper-proof way. Transactions are linked to each other, forming a chain of blocks. If the majority of network participants agree on the blockchain's status, changes to the data are impossible without everyone's acknowledgment. This contrasts with traditional centralized systems, where a single entity controls the database and can change it at will. The integrity ensured by blockchain technology, therefore, makes it markedly more secure and reliable (El Bassam, 2021).

2.2.1.3 Privacy

Each user can interact with the blockchain using a generated wallet address that does not reveal the user's identity. Nevertheless, blockchains cannot provide complete privacy protection due to natural constraints. In a permissionless blockchain architecture, all parties have the authority to access the ledger, which implies they can reveal the entire history of recorded transactions (Z. Zheng et al., 2017). To address these challenges and ensure privacy and anonymity, various mechanisms and techniques have been developed. To address these challenges and to ensure privacy and anonymity, various mechanisms and techniques have been developed, all of which aim to increase privacy. For instance, Zero Knowledge Proof (ZKP) is a cryptographic method that can be integrated into blockchain systems to augment privacy. ZKP permits users to preserve complete authority over their data. It enables individuals to confirm the truthfulness or correctness of information without risking the confidentiality of the actual content. Thus, zero-knowledge proof represents a robust mechanism for protecting privacy when conducting transactions and interactions within blockchain networks, as explained by Korkmaz et al., (2019).

2.2.1.4 Transparency

Transparency is accomplished via blockchain, which shares transaction information with all participants engaged in those transactions. In a blockchain ecosystem, the presence of a third party is unnecessary, increasing the accessibility of transactions and ensuring a reliable workflow. Blockchain transparency ensures that all transactions on the blockchain can be seen by everyone involved (El Bassam, 2021). Transparency provides a clear understanding of the present state of the ledger. Moreover, members have the ability to monitor data using verifiable timestamps, as various blockchain algorithms allow access to records in a database. This attribute enhances the trustworthiness and accountability of blockchain technology (Montecchi et al., 2019).

2.2.1.5 Traceability

Blockchain technology enables data traceability by timestamping added or updated information in the system. The timestamp technology adds a temporal dimension to each data block, and the hash values stored in each block accurately identify both the current block and its parent block. This guarantees a transparent and verifiable record of the chronological order and integrity of data transactions within the blockchain system (Xinyi et al., 2018). Data traceability monitors the origin, destination, and sequence of updates that data undergoes between nodes. Data traceability is essential for maintaining data integrity and fostering a higher level of trust in information and offers several additional benefits, including improved data governance, regulatory compliance, understanding the impact of changes, and improving data quality (Bhutta et al., 2021a).

2.2.2 Architecture of Blockchain

The architecture of blockchain comprises essential elements for its decentralized nature and security. A peer-to-peer network enables direct communication, while cryptographic tools like hash functions and Merkle trees ensure data integrity. Digital signatures verify participant authenticity, and timestamps organize transaction chronology. Different node types, such as miners and validators, perform different roles, and consensus mechanisms dictate the rules of agreement. This section is an overview of the fundamental components.

2.2.2.1 Peer-to-Peer Network

In a Peer-to-Peer Network (P2P), users share resources such as processing power, storage space, and network bandwidth directly with others (Figure 11). Each device in the network acts as both a client and server, enabling it to request and provide resources. This eliminates the need for a central server, making the network more resilient and scalable (Bhutta et al., 2021a). For instance, should an attempt be made to download a file from another user on the P2P network, your device can contact that user's device directly to request the file. Once the data is transferred successfully, the individual's device may then proceed to provide the file to other users who request it. The utilization of this peer-to-peer sharing model establishes P2P networks as an optimal solution for file sharing, content delivery, distributed computing, and cryptocurrency applications (Schollmeier, 2001).

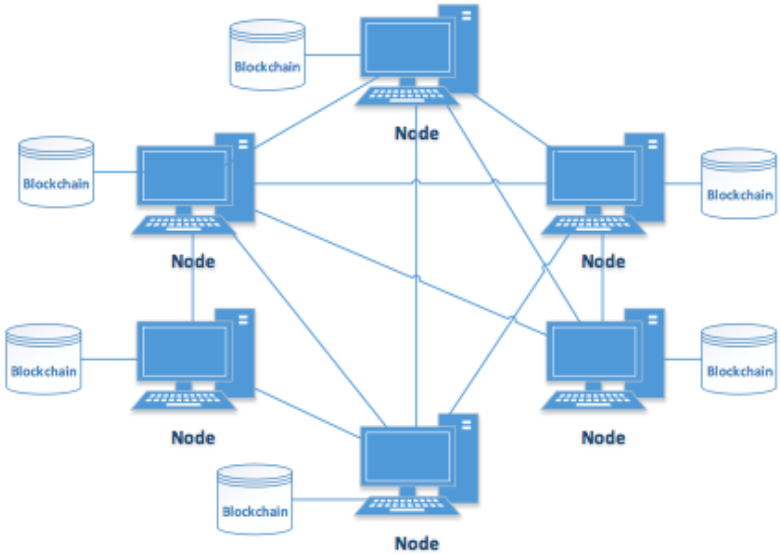

Figure 11. Peer-to-Peer Network (Koteska et al., 2017)

2.2.2.2 Hash

A hash is a special mathematical function that protects the integrity of data. It converts any type of data into a unique value of a fixed size, called a "hash value". This function is one-way, meaning that it is impossible to reverse the process and recover the original data from the hash value. This one-way property makes hashes very secure and makes the hash value a reliable representation of the input data without revealing the actual content (Bruce, 1996). Hash functions allow the mapping of given data to a hash of a predetermined length. The size or length of the output hash is not dependent on the input length. A hash can be considered a distinctive "signature" for a given text, providing a unique identifier for the given data (Aslam et al., 2020).

2.2.2.3 Merkel Tree

A Merkle tree, also known as a hash tree, is an efficient and secure way of verifying data, in which the data and corresponding hash values are arranged in a tree. In a Merkle tree, each leaf node is labeled with the hash value of some data, and each non-leaf node contains the hash value of its child nodes (Bhutta et al., 2021b). They are commonly associated with digital currencies. However, their applications extend beyond this scope. Their hash-based nature makes them well-suited for various cryptographic applications (Bosamia & Patel, 2018). The structure of the Merkle tree is shown in Figure 12, where it contains transactions ABCD and their corresponding hashes. The bottom nodes represent leaves, intermediate hash nodes represent branches, and the top hash represents the Merkle root. This figure shows that as you move from the leaf nodes to the Merkle root, the number of hashes computed is proportional to the logarithm of the number of leaf nodes (Plevris et al., 2022). In other words, the hash lists have a number of hashes proportional to the logarithm of the number of leaf nodes (Bosamia & Patel, 2018).

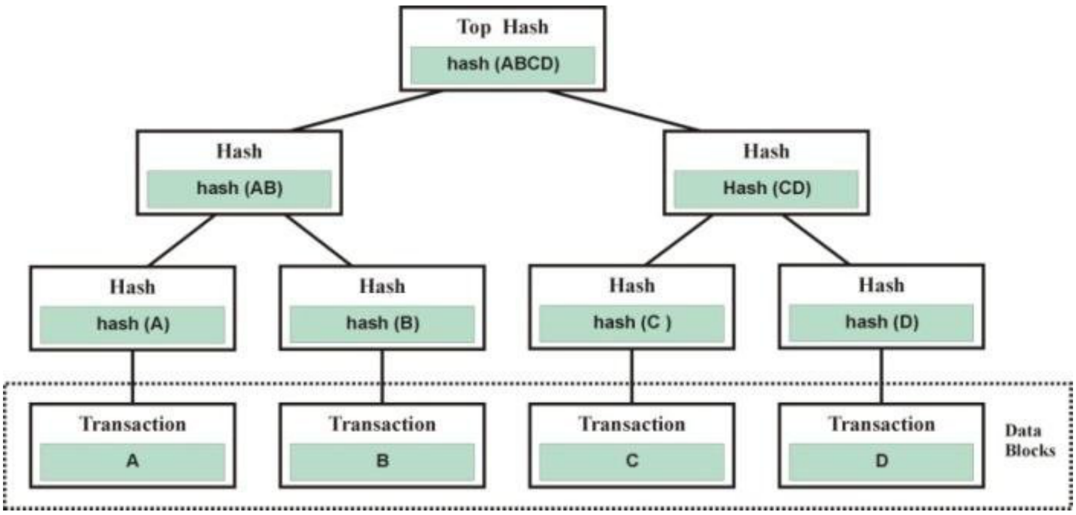

Figure 12. Example of A Markle Tree (Bosamia & Patel, 2018)

2.2.2.4 Digital Signatures

Digital signatures serve as digital stamps that establish the identity of the document's creator and guarantee its authenticity. These signatures are typically created using public key cryptography, where the signer uses his or her private key to sign the document, and the recipient can verify the signature using the signer's public key. A public key serves as a publicly available identifier for an entity. A private key, on the other hand, is a confidential key that is mathematically linked to the user's public key (Panda et al., 2021). Digital signatures are considered to be authentic, unverifiable, irreversible, and non-repudiable. This means that a digital signature cannot be transferred to another document, that only the original signer can falsely claim to have signed it, and that even the original signer cannot deny having signed it. Creating a digital signature requires a pair of private and public keys, a timestamp, and a hash function. The digital signature process is outlined in Figure 13. A cryptographic signature is generated by combining the document's content, the issuer's private key, and a timestamp to establish the validity and non-repudiation of a digital document. In the context of blockchain, this data also includes the sender's private key, the receiver's public key, a record of the receiver's performance, and a timestamp. A hash function, such as SHA256, is applied to this combined data, creating a unique and fixed-length hash value. This hash value is then stored in the blockchain, a secure and tamper-proof distributed public ledger. Storing the hash value on the blockchain ensures that the signature and associated document remain immutable and can be easily verified (Palma et al., 2019).

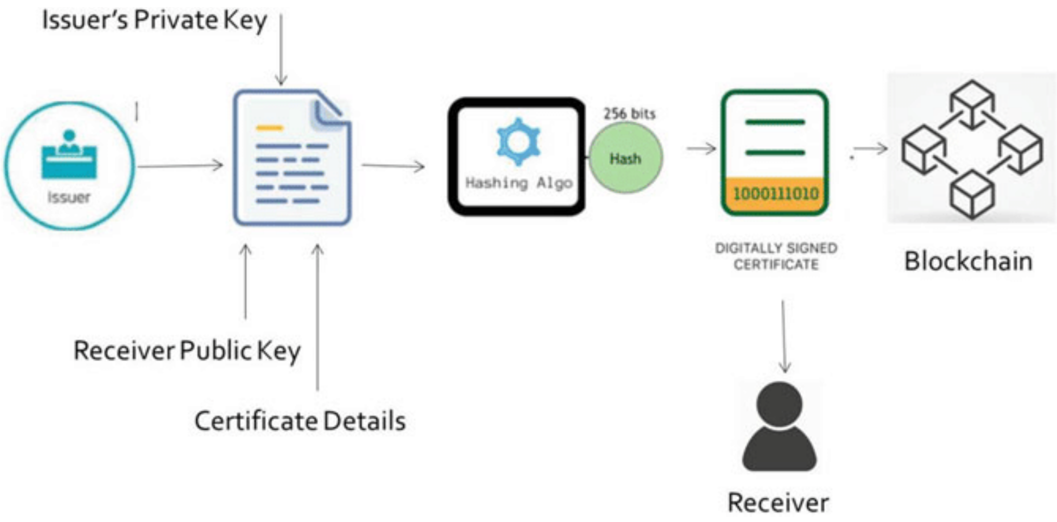

Figure 13. Digital Signature Framework on Blockchain (Panda et al., 2021)

2.2.2.5 Timestamp

A timestamp refers to the time at which an event is recorded by a computer. It represents the moment at which the record is created, rather than the time of the event itself. The data associated with this timestamp is consistently recorded alongside the actual data, making it easy to compare two different records and track progress over time (Bhutta et al., 2021a). Timestamping is a critical security feature, especially in the context of digitally signing documents. It involves associating a digital signature with a specific timestamp, providing an additional layer of security and authenticity. This ensures that the signature is associated with a specific point in time, making it more resistant to tampering and enhancing the overall integrity and legal validity of the document. Timestamping helps establish a clear chronological sequence for digital signatures and contributes significantly to the reliability of signed legal documents (Palma et al., 2019).

2.2.2.6 Node

Blockchain networks usually have two primary types of nodes: full nodes and lightweight nodes. Each type performs a unique function in ensuring the network's integrity and effectiveness (Bhutta et al., 2021a). In summary, after submitting a transaction, the network sends it to a specific node (user) or set of nodes. However, this doesn't automatically mean that the transaction is added to the blockchain immediately. In fact, the transactions enter a queue within the publishing node and are added to the blockchain when that node successfully publishes a block. The process involves sequentially incorporating transactions into blocks, which are added to the blockchain (Panda et al., 2021).

2.2.2.6.1 Full Node

A full node in the blockchain network is a node that is fully functional and acts as a server. It can store a complete copy of the data and history of the blockchain nodes. The full node has a key role in maintaining consensus among other nodes by applying consensus algorithms and verifying transactions as they occur within the blockchain network. It also actively participates in future policy and decision-making processes within the blockchain network (Bhutta et al., 2021a).

2.2.2.6.2 Lightweight Node

Lightweight nodes, on the other hand, maintain a compressed version of the blockchain, usually storing only block headers and recent transactions. This smaller amount of data enables lightweight nodes to operate on less powerful devices and consume fewer resources. S. Banerjee et al., (2023) discussed the lack of incentives for full nodes dispensing their services to lightweight clients, as well as the rewards given to lightweight nodes. The authors recommend the implementation of smart contracts to provide a fair deployment arena in the blockchain network.

2.2.2.7 Consensus Mechanisms

In a decentralized environment, blockchain technology eliminates the dependence on a single, centralized authority for trust and verification. It utilizes decentralized consensus mechanisms to ensure the reliability and consistency of data and transactions. These mechanisms allocate the responsibility for validating transactions and upholding the network's integrity among all participants, leading to a more secure and sturdy system (Kiayias et al., 2017). Different blockchain platforms have put forward and employed various consensus models, each having its own advantages and drawbacks (Bhutta et al., 2021a). Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), and Delegated Proof of Stake (DPoS) are four common consensus mechanisms used in blockchain technology (Z. Zheng et al., 2018). In this part, common consensus mechanisms have been reviewed and examined. In Table 1, consensus algorithms, which are widely used in comparison, are given.

Table 1. Consensus Algorithms Comparison (S. Zhang & Lee, 2020)

Property	**PoW**	**PoS**	**PBFT**	**DPoS**
Node	Open	Open	Permissioned	Open
Energy Saving	No	Partial	Yes	Partial
Power Consumption	Large	Less	Negligible	Less
Scalability	Good	Good	Bad	Good
Tolerated power of adversary	<25% computing power	<51% stake	<33.3% faulty replicas	<51% validators

2.2.2.7.1 Proof of Work (PoW)

Proof of Work (PoW) is termed as one of the fundamental consensus models for Blockchain technology. The main idea of PoW is to compete to generate new blocks in the Blockchain based on computational power (Bhutta et al., 2021a). This algorithm requires the miner to perform a computation and produce a value. The underlying principal centers around a competition among participants to create the next block in the blockchain. The selection process relies on computational power, resulting in a competitive race. The consensus mechanism determines that the hash value computed must be lower than or equal to a predetermined value for the block to be recognized as valid. This process involves miners adjusting the nonce and recalculating the hash to meet specific criteria and compete to create a new block within the blockchain. Once the block is successfully validated, other miners add it to their individual blockchains. This process guarantees agreement on the block's validity before it becomes part of the shared blockchain across the network (Z. Zheng et al., 2017).

2.2.2.7.2 Proof of Stake (PoS)

In Proof-of-Stake (PoS) consensus mechanisms, a node's probability of being selected to validate a block and receive rewards is determined by the amount of cryptocurrency it has staked. This system incentivizes ownership and participation in the network for users with a larger stake, effectively encouraging investment in the cryptocurrency and using their stake to increase their opportunities to create blocks and reap rewards (Kiayias et al., 2017). The main benefit of the Proof-of-Stake protocol is that it does not require nodes to invest in expensive mining equipment for operations (Bhutta et al., 2021a).

2.2.2.7.3 Delegated Proof of Stake (DPoS)

An advancement of the PoS algorithm, called Delegated Proof-of-Stake (DPoS), is outlined in the study by Zhang & Lee, (2020). This method employs stakeholder voting to select the witness node responsible for creating blocks in the blockchain. The chosen witness node earns incentives for block creation, but a failure to produce a block lead to exclusion from future voting procedures. This mechanism aims to streamline and enhance accountability in block creation within the DPoS consensus framework (Bhutta et al., 2021a). It is a more energy-efficient and scalable consensus mechanism than PoW and PoS. This is because DPoS avoids the need for miners to solve computationally complex puzzles at great energy expenditure. Instead, stakeholders vote for delegates who validate transactions and create new blocks. This method is much less energy-intensive than PoW and also offers greater scalability (S. Zhang & Lee, 2020).

2.2.2.7.4 Practical Byzantine Fault Tolerance (PBFT)

Practical Byzantine Fault Tolerance (PBFT) is a consensus algorithm developed as a solution to The Byzantine Generals Problem. Byzantine Generals is a game theory illustration of how to achieve consensus in a decentralized system that does not rely on a trustworthy central authority. Byzantine Fault Tolerance (BFT) originated from this dilemma and is a distributed network characteristic that achieves agreement on a shared value, even when certain nodes fail to respond or provide erroneous information. BFT enables a distributed network to reach consensus despite nodes that fail to respond or provide incorrect information. The objective of a BFT mechanism is to provide protection against system failures by employing collective decision-making that includes both correct and faulty nodes, with the goal of minimizing the influence of the faulty nodes. The intention is to improve the resilience and reliability of the distributed network (Bhutta et al., 2021a). (Castro & Liskov, 1999) have proposed the PBFT algorithm to handle

Byzantine faults. To effectively withstand Byzantine faults on an asynchronous network, they have introduced a protocol for state-machine replication. The main objective is to implement BFT in a distributed file system.

2.2.2.8 Types of Blockchain

There are several commonly used blockchain types. These can vary depending on the use cases and the features needed. The most common blockchain types are public blockchain, private blockchain, and consortium blockchain. Public blockchains operate transparently, enabling all users to observe recorded transactions and participate in the consensus mechanism. Conversely, consortium blockchains restrict participation in the consensus process to a select group of pre-approved nodes, while private blockchains limit access exclusively to nodes authorized by a specific organization (Z. Zheng et al., 2017). This section examines these blockchain types.

2.2.2.8.1 Permissionless or Public Blockchain

In a public or permissionless blockchain, individuals do not need any authorization to join the network (Cai et al., 2018). This type of blockchain is fully decentralized, enabling participants to participate in the consensus process, send and read transactions, and maintain the shared ledger. All nodes can validate, access, and publish new blocks, enabling them to keep a complete copy of the entire blockchain (Bhutta et al., 2021a). As a result, anyone with internet access can explore the public blockchain. The Bitcoin public blockchain was one of the earliest of its kind, allowing for the decentralized execution of transactions via a freely accessible network (Asmare et al., 2023). Table 2 shows the common advantages and disadvantages of public blockchains.

Table 2. Public Blockchain Advantages and Disadvantages

Public Blockchain Advantages and Disadvantages		
Advantages	Trustable	Public blockchain nodes do not need to know or trust each other since the proof-of-work procedure guarantees the absence of fraudulent transactions.
	Secure	A public network can accommodate an indefinite number of participants or nodes, increasing its security. As the network grows in size, the number of records distributed increases, making it harder for hackers to hack the entire network.
	Open and Transparent	The information on a public blockchain is visible to all member nodes. Each authorized node has a record copy of the blockchain, or digital ledger.
Disadvantages	Lower TPS	The amount of transactions per second (TPS) in a public blockchain is often quite low. This limit is due to the size of the network, which involves many nodes that take time to verify transactions.
	High Energy Consumption	The proof-of-work mechanism is costly and consumes a significant amount of energy. Clearly, technology will need to develop energy-efficient consensus methods.
	Scalability Issues	The processing and completion of transactions in public blockchains can be relatively slow, which poses challenges for scalability. As the network size increases, the speed of transaction processing tends to decrease

2.2.2.8.2 Permissioned or Private Blockchain

In a private blockchain, access control is implemented to ensure that the blockchain operates within the confines of a specific organization. Participants must receive an invitation, and current participants may contribute to the decision-making process for future participants. After joining the network, entities participate in maintaining the blockchain in a decentralized fashion. Additionally, the trustworthiness of the network is reinforced by the internal participants' honesty in verifying transactions on private blockchains (Cai et al., 2018). Furthermore, permissioned blockchains are widely considered to be more secure and efficient than public blockchains due to the limitation of network access to known participants. Cryptographic hashes and participant consensus also protect against tampering, similar to public blockchains. However, unlike public blockchains, nodes in permissioned blockchains are not anonymous. Network security and accountability are enhanced by the identifiable nature of permissioned blockchain participants (Bhutta et al., 2021a). The typical advantages and disadvantages of public blockchains are listed in Table 3.

Table 3. Private Blockchain Advantages and Disadvantages

Private Blockchain Advantages and Disadvantages		
Advantages	Speed	Private blockchain transactions are typically faster as a result of having a smaller number of nodes within a private network. The decrease in node count results in a shorter transaction verification time.
	Scalability	Indeed, private blockchains provide scalability benefits as organizations can adjust the size of their blockchain to meet specific needs. This flexibility enables organizations to scale private ledgers as needs change.
Disadvantages	Trust Building	In a private network, the number of participants is lower compared to a public network.
	Lower Security	Blockchains that have a limited number of nodes or members are vulnerable to security threats.
	Centralization	They are limited as they require a centralized Identity and Access Management (IAM) system to operate. This system provides full administration and monitoring functions but it can be seen as a limitation with regard to decentralization.

2.2.2.8.3 Consortium Blockchain

Consortium blockchains are a type of private blockchain designed for use by multiple organizations. Only trusted and invited participants are allowed to join and maintain the network (Bhutta et al., 2021a). While consensus in consortium blockchains is slower than in private chains, it is faster than in public ones. In terms of security, consortium blockchains employ advanced measures to prevent tampering with information compared to private blockchains. The involvement of participants from multiple organizations enhances the effectiveness of security measures, resulting in more robust protection against hacking attempts (Cai et al., 2018). Table 4 lists the typical advantages and disadvantages of consortium blockchain systems.

Table 4. Consortium Blockchain Advantages and Disadvantages

Consortium Blockchain Advantages and Disadvantages		
Advantages	Secure	A consortium blockchain is considered more secure, scalable, and efficient than a public blockchain network due to the utilization of access controls. Private and mixed blockchains also use access controls to enhance security.
Disadvantages	Lack of Transparency	The consortium blockchain has limited transparency. If a member node is infiltrated, it can still be compromised, and the rules of the Blockchain can cause the network to become unworkable.

2.2.3 Evolution of Blockchain

The evolution of blockchain technology has led to the development of three different versions: Blockchain 1.0, 2.0, and 3.0, each designed for different types of implementations.

Blockchain 1.0 primarily concentrated on virtual currencies, with Bitcoin leading the way (Mainelli & Smith, 2017). This set the stage for examining the potential of digital currencies to reduce expenses against traditional currencies. Thus, Blockchain 1.0 offers distinct benefits compared to conventional payment methods, such as reduced transaction costs and a certain level of transactional confidentiality. In addition, bitcoins address the concern of double spending, thus reducing fraudulent activities by enabling secure, traceable, and transparent transactions (Panda et al., 2021). During this phase, several blockchain applications emerged centering on digital currencies and their application in diverse sectors such as payments and foreign exchange. Essentially, Blockchain 1.0 mainly focused on cryptocurrency and payment systems constructed within cryptocurrency ecosystems (Xu et al., 2019).

Blockchain 2.0 represents a significant milestone in the evolution of the blockchain industry, characterized by the emergence of "smart contracts", which automate and facilitate trusted contractual agreements, enabling a new range of decentralized applications and services (Bhutta et al., 2021a). Smart Contracts are computer programs that execute automatically based on predetermined clauses between two parties. These contracts cannot be hacked or tampered with, significantly reducing costs related to verification, execution, and fraud prevention (Panda et al., 2021). Unlike traditional paper contracts, smart contracts operate without intermediaries and rely on a peer-to-peer approach for direct action (Varfolomeev et al., 2021). For example, Ethereum, Codius, and Hyperledger have established programmable contract language and executable infrastructure to implement smart contracts (Xu et al., 2019).

Blockchain 3.0 is a platform that enables the construction of secure and distributed applications for various industries beyond the financial markets. It integrates with web technology, creating a universal and global reach. This platform contributes to developing the "Smart World," specifically in allocating resources for the physical world and human assets (Ali et al., 2019). It encompasses multiple technological advances, such as smart property, decentralized applications (Dapps), decentralized autonomous organizations (DAOs), and decentralized autonomous corporations (DACs), as introduced by Swan, (2015).

2.2.4 Blockchain Technology in The Construction Industry

The construction industry is undergoing significant change, characterized by technological advancements and an increasing emphasis on sustainable and efficient practices. Among the innovations set to transform various aspects of the construction sector is blockchain technology, a decentralized and secure digital ledger. Integrating cutting-edge technologies such as IoT, BIM, and AI with Blockchain technology holds tremendous promise for overcoming the limitations in the construction industry (Mahmudnia et al., 2022). The potential applications of blockchain technology are expected to broaden as it matures. The capacity of technology to increase transparency, automate processes, and enhance traceability is generating prospects for a more productive, environmentally friendly, and cooperative construction ecosystem.

The initial research papers on implementing blockchain technology in the construction sector were released in 2017 and have since then continued to grow at a high rate. Scott et al., (2021) comprehensively surveyed the majority of these studies. In this literature review, the study identifies and organizes 33 distinct categories of blockchain applications in the construction industry across seven topic areas: procurement and supply chain, design and construction, operations and lifecycle, smart cities, smart systems, energy and carbon footprint, and decentralized organizations. These findings offer valuable insights for professionals interested in utilizing blockchain technology for construction-related purposes. Furthermore, Mahmudnia et al. (2022) conducted a study on blockchain features to analyze their impact on mitigating disputes in the construction industry. A systematic review of publications is conducted to present a comprehensive classification of blockchain-enabled applications in construction dispute management. The study identifies gaps in research and opportunities for future work in the construction field.

2.2.4.1 Procurement and Supply Chain

Procurement and supply chains in the construction industry are suitable for blockchain applications, and many studies have been conducted on them. Blockchain technology promotes data governance in the supply chain, providing authentication, confidentiality, and access control for various services. Additionally, its integration with IoT and RFID devices strengthens security measures by offering robust consensus mechanisms for dynamic data storage. This combination encourages transparency and data protection and optimizes reliability and cost management (Dutta et al., 2020). Through the application of blockchain technology, construction progress can be monitored, as well as traceability throughout the supply chain. It also enables the implementation of an automated payment system based on predetermined contract milestones (Piew, 2020). Also, Dutta et al., (2020) conducted a comprehensive study on integrating blockchain technology into supply chain management, highlighting several critical areas where blockchain can improve performance. These include establishing an immutable record of completed tasks supported by irreversible data, protecting against network failures, improving data synchronization, strengthening data integrity, automating business processes using smart contracts, and improving product revision tracking.

2.2.4.2 Design & Construction

The focus on integrated project management in design and construction has stimulated discussions on the applicability of blockchain. According to Yang et al., (2022), blockchain's implementation through a case study resulted in improved reliability and efficiency in scaffolding work. Additionally, Erri Pradeep et al., (2021) indicate that blockchain can address design liability issues and enhance security. Moreover, the slow adoption of BIM is often attributed to the lack of traceability in model revisions, relying on manual data entry and designer trust.

Challenges arise in centralized cloud systems when dealing with simultaneous updates in a project, and these challenges are exacerbated when integrating BIM with blockchain due to bandwidth limitations stemming from blockchain's consensus properties (Scott et al., 2021). To address these issues, R. Zheng et al., (2019) proposed a mobile app that leverages blockchain to verify the latest BIM model version through hash comparison, providing users with a verification receipt. Another case study explored how accurately logging geometry and volume in BIM models can be translated into computable code for smart contracts (Mason, 2019). These studies suggest that implementing blockchain in project management could improve stakeholder collaboration.

2.2.4.3 Circular Economy and Lifecycle Assessment

The inherent architecture of blockchain technology, with its decentralized and distributed nature, makes it a powerful tool for enabling the CE and improving life cycle assessment (Corsini et al., 2023). It eliminates the need to rely on central authorities and ensures data transparency across the web, allowing stakeholders to track the journey of assets, materials, and products with unprecedented accuracy. This increased transparency establishes the basis for effective resource management, fostering sustainability and completing the CE loop. Shojaei, (2019) proposed a method for precisely tracking the raw materials throughout their lifecycle using blockchain technology. This solution involves incorporating detailed metadata about the materials into a blockchain, allowing for continuous tracking from extraction to end use. Copeland & Bilec, (2020) outlined a framework that combines RFID, BIM, and blockchain technologies to create a comprehensive digital footprint for components throughout their lifecycle in the building sector. This approach employs sensors to collect data during crucial stages, such as installation, decommissioning, and origin information. In contrast, metadata containing supplier, manufacturer, and handling information is stored together with the component data. With blockchain providing support for data validation, the framework also aims to integrate a crypto-economic incentive system to encourage asset recycling. This multifaceted approach aims to enhance traceability, transparency, and sustainability in component management, presenting a secure and authentic account of their journey from production to recycling. When combined with IoT and big data analytics, blockchain technology offers a robust solution to the challenge of collecting reliable data in Life Cycle Assessment (LCA) for supply chain sustainability. Also, A. Zhang et al., (2020) present a framework to guide the implementation of a blockchain-based LCA. The framework suggests a system architecture that incorporates the utilization of Blockchain, IoT, as well as big data analytics and visualization. Another important study by Shojaei et al., (2021b) explores the potential of blockchain technology to drive CE in the built environment. Their paper introduces and tests a blockchain model through a synthetic case study, providing a proof of concept for the feasibility of blockchain as a facilitator of CE in the built environment. The authors argue that the current status of each material and component can be tracked and proactively planned for reusability through the use of blockchain. The research highlights that blockchains can deliver noticeable improvements in the management and sustainability of materials in the built environment.

CHAPTER 3

METHODOLOGY

This chapter outlines the methodology used in this thesis. The methodology consists of 5 main parts. In the first part, the barriers to CE in the construction sector were tried to be identified. For this purpose, a literature review was conducted focusing on the information flow of CE in the construction sector. Afterward, interviews with experts were conducted and the overall concept and critical information flow practices for CE were questioned. Then, the results of the studies were analyzed. Then, based on the obtained data as a result of these assessments, a framework is presented that aims to enhance the transition to CE and increase circular collaboration and awareness in the construction sector. Lastly, a case study was conducted to test and validate this framework. The main parts of the methodology are shown in Figure 14. Details of these parts are presented in this section.

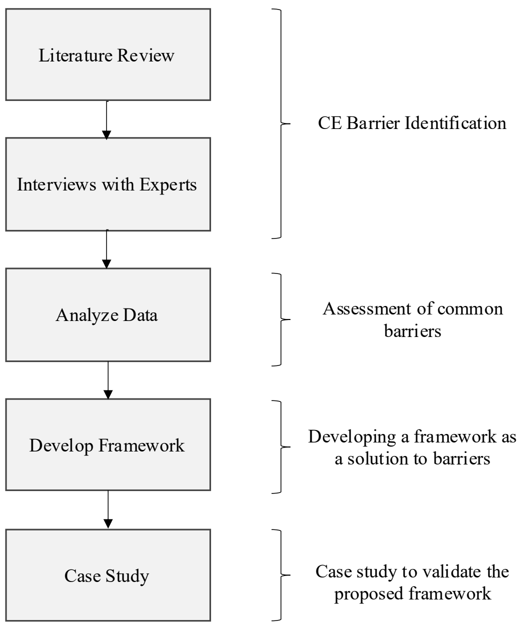

Figure 14. Main Parts of the Methodology

3.1 Circular Economy Barriers Identification

A thorough review of the literature was carried out with a focus on the flow of information in the construction industry for CE. Following this, experts were interviewed to question the overall concept and critical practices of information flow for CE. These interviews also contributed to understanding the relationships between construction stakeholders. This section describes the processes of identifying barriers and determining the information flow between stakeholders.

3.1.1 Literature Review

In order to identify barriers to implementing CE principles in the construction industry, a thorough literature review was conducted. The study specifically analyzed information sharing and cultural barriers that could hinder the adoption of CE practices. The review pointed out several obstacles, such as a lack of awareness about CE principles, challenges in keeping track of material information, limited access to data, and a need for better standardization of CE principles.

3.1.2 Interviews with Experts

Semi-structured interviews were used to gather the data needed to identify barriers to CE adoption in the construction industry. During the eight months of face-to-face meetings, many views and information were gathered. In these interviews, material information flow, stakeholder relations in the construction sector and possible barriers were examined for CE adaptation. An example of the conceptual framework presented is planned to be adapted in the field of industrial steel construction. Therefore, interview participants were selected as stakeholders in the industrial steel construction supply chain. Meetings were held with a construction company, two steel material suppliers, two clients, and a steel metal recycling companies to interview 12 senior experts and practitioners. The selected participants had blockchain knowledge and experience. Table 5 shows the positions and sector experience of the participants. Prior to the interviews, consent was obtained from all participants due to research ethics.

Table 5. General Information About Experts

#	Stakeholder	Position	Experience
1	Supplier 1	Planning Manager	11
2	Supplier 1	Production Systems Manager	13
3	Supplier 2	Melt shop Manager	14
4	Supplier 2	Production Manager	13
5	Construction Company 1	Environmental Engineer	5
6	Construction Company 1	Supply Chain Manager	12
7	Construction Company 1	FAT Manager	15
8	Construction Company 1	Procurement Manager	12
9	Material Recycling Company 1	Quality Inspector	17
10	Material Recycling Company 1	Grapple Operator	12
11	Client 1	Inspector	15
12	Client 2	Civil Engineer	7

Semi-structured interviews were conducted with a group of experts during the research study. The interview questions were predetermined, but the experts were also encouraged to share their spontaneous opinions and insights beyond the given questions. The questions that were asked to each expert are listed in Table 6.

Table 6. Semi-Structure Interviews Questions

#	Questions
1	What do you think about the adaptation of the construction industry to the circular economy?
2	Are you familiar with the concept of circular economy, and does your company have this culture? What is your opinion?
3	What challenges do you face to adapt to the circular economy?
4	What improvements in these processes could strengthen the transition to a circular economy?
5	Do you trace manufacturing/supply/construction and other processes waste or scrap?
6	How can scraps generated during the process be reduced/recycled and reused?
7	Is the data of the waste in these processes recorded? How?
8	Are energy consumption and carbon dioxide emissions data recorded? How?
9	Can you describe your company's role in the construction process? How do you ensure the information flow that can contribute to CE in industrial steel construction?

The interviewees represented various stakeholders involved in the construction process and were asked to provide their views on various aspects of the steel construction industry's adaptation to CE principles. The experts were asked general questions about the current situation, including the barriers to adapting to CE, and potential solutions for more sustainable processes.

3.2 Assessment of Circular Economy Barriers

The purpose of this step is to identify the barriers found in the literature review. This involves a thorough review of the information to determine which barriers to focus on. Additionally, the results obtained from the expert interviews conducted after the literature review were evaluated for compatibility with the literature.

3.3 Developing the Framework

At the end of the studies, a conceptual blockchain-based framework for the flow of information was developed to address the barriers to CE that were assessed. This framework is intended to be a solution to the identified CE barriers. There are several important considerations in developing this framework, such as model structure, the type of blockchain used and why, ensuring accountability and transparency in the transferred information, participants and their authorities, and establishing a reliable data collection process. In addition, an example of the developed framework in industrial steel construction is provided for better understanding. The framework is exemplified in the field of industrial steel construction for better understanding. However, it can also be designed for other areas of construction.

3.4 Testing and Validation with a Case Study

The thesis presents a conceptual framework as a solution to the evaluated CE problems. It is advocated that this framework can increase CE compliance in the construction sector. Hence, a small-scale case study was conducted to assess the validity of this approach.

The case study was carried out in an industrialized EPC company established in 1955. The large-scale company has engineering and production facilities in Turkey with 1600 qualified employees. It has an annual steel production of approximately

285 tons and constantly exports its products worldwide. It provides the engineering, construction, and manufacturing services of steel towers, poles, and high masts, especially for power transmission and distribution infrastructure.

Five experts working in the company mentioned in the case study were interviewed. These participants were selected from experienced employees who were familiar with the relationships with other stakeholders associated with the company. Firstly, the example blockchain-based information flow framework presented in this thesis was explained to the participants. They were then asked to evaluate and rate this framework. The framework was scored in five categories on a scale of 0-5, assessing its applicability and potential for adaptation to CE in the construction industry. These categories are applicability, records of CO_2 emission and energy consumption, CE awareness, culture and cooperation, standardization in the field of CE, and material information traceability.

CHAPTER 4

FINDINGS

This section presents the findings from the literature review and semi-structured interviews that were conducted to identify the barriers to CE adoption in the construction sector. It also highlights the parallels between these two studies and the barriers they focused on.

4.1 Findings From the Literature Review

The transition to CE in the construction sector has been hindered by various obstacles, as highlighted in several studies in the literature. These shortcomings have resulted in slower progress towards achieving a circular construction economy. This section presents the findings of the comprehensive literature review.

According to Adams et al., (2017), limited awareness, interest, and culture are major challenges to implementing CE principles in the construction industry. They surveyed CE barriers. As a result of the survey, lack of interest was seen as a significant challenge by respondents with more experience in construction. Furthermore, the survey indicated confusion around the meaning of the CE and related terms such as reuse and recycling, highlighting the need for greater clarity and precision. Hart et al., (2019) mention that the construction industry faces a number of barriers when it comes to adopting CE practices, and many of them are rooted in social and cultural factors. These challenges stem from the industry's longstanding reliance on linear production models, as well as a lack of awareness and collaboration among various stakeholders. In traditional construction firms, conventional practices often hinder the effective implementation of CE principles, which require strong partnerships and collaboration. This problem is compounded by the fact that different stakeholders may have conflicting priorities or approaches.

Also, Hart et al., (2019) found that different issues make it hard for the AEC industry to transition to CE practices. These barriers are rooted in the established practices of the linear economy, attitudes towards ownership and status, and a silo mentality that hinders collaboration and integration. These findings highlight the need for strategies to address these issues in order to facilitate the transition to CE in the AEC industry. Hartley et al., (2020) pointed out that a major obstacle to adapting CE in academic research is that it lacks a regular framework. This issue is compounded by the lack of a globally accepted agreement on how to promote the CE through policy. Additionally, their analysis by Giorgi et al., (2022) reveals that while there has been a high level of policy application to promote CE principles, there is still a low level of sustainability control. Specifically, there is a lack of established and widely promoted organized systems for traceable material flows, as well as the use of supporting tools for the control of materials. These findings emphasize the need for increased attention and action to facilitate the development of more robust mechanisms for material tracking and control to ensure the effective implementation of sustainable practices in the CE. Moreover, Densley Tingley et al., (2017) conducted a series of semi-structured interviews with participants across the UK construction supply chain to identify barriers to implementing CE practices. A study revealed that interviewees considered several barriers to be significant, including cost, availability/storage, lack of client demand, supply chain gaps/lack of coordination, and particularly, the traceability of material information. These findings highlight the need to develop and promote systems for the traceability of material in the construction industry to facilitate the effective implementation of CE practices. CE requires a coordinated effort from all stakeholders to achieve sustainable outcomes with conscious communication and commitment. Therefore, organizational consciousness, which involves awareness and responsibility for sustainable practices, is essential for successfully adopting CE in businesses (B. K. Ababio & Lu, 2023).

Collectively, these studies in the literature clearly show that there is a lack of awareness of circularity, a lack of material information traceability, and a lack of collaboration and standardization in the construction sector. These barriers slow down and hinder the transition to CE in the construction sector. Table 7 shows the barriers collected from literature review.

Table 7. Barriers from Literature Review

#	**Barriers to Adaptation of Circular Economy**
1	Lack of awareness, culture, and collaboration
2	No adequate standardization
3	Lack of material information traceability

4.2 Findings from Interview with Experts

As part of the research, data was collected through semi-structured interviews to understand practices for CE adoption in the construction industry. The interviews provided a wealth of insights and information covering various aspects of CE dimensions, including the life cycle of materials and stakeholder relationships in the construction sector. As the example conceptual framework was adapted for use in industrial steel construction, the targeted participants for the interviews were stakeholders in the industrial steel construction supply chain. This section presents the findings from the interviews.

The responses to the questions asked in Table 6 and expert opinions are as follows;

The responses given by the experts to questions 1 and 2 indicate that they are familiar with understanding the CE concept. Their approach towards CE emphasizes the importance of sustainable practices such as keeping materials in use for as long as possible, extracting maximum value from them throughout their entire life cycle, and minimizing waste. However, they have expressed their disappointment in the fact that the companies they work for have not fully embraced the culture of the CE. Despite their best efforts, they have found it challenging to implement sustainable practices due to a lack of support from their respective organizations. Additionally, they have identified a general lack of awareness within the construction sector as a significant barrier to the adoption and spread of CE culture.

For question 3, in summary, the challenges they face are upfront cost, lack of standardization, limited cooperation, low level of awareness, and culture and material information monitoring for adopting CE. One of the respondents, an environmental engineer, states that the transition to CE practices often requires upfront investments in technology, research and development, and training. Furthermore, almost all respondents said that many stakeholders in the construction sector are not fully informed about the benefits and principles of CE. According to expert opinion, there is a need for greater awareness to clear up misconceptions and to encourage collaboration for CE practices.

The experts' opinions and suggestions on which improvements in production and construction processes could strengthen the transition to CE were collected during the interview. In question 4, they were asked for additional ideas they would like to express. Experts add that verifying the suitability of materials for reuse or recycling can be difficult without information on their origin and history. A lack of such information can undermine confidence in recycled materials and potentially discourage their use. They, therefore, suggested that increasing the traceability of material information could accelerate the transition to CE. Furthermore, a FAT manager from a construction company said that their customers have requests for recycled materials and want to have access to this information transparently. He argues that a transparent flow of information could contribute to CE.

According to the responses provided for questions 5, 6, and 7, it has been observed that experts in the field of waste and scrap management tend to closely monitor and track these materials throughout the entire production process. Their findings reveal that this critical data is typically recorded and stored within the SAP system. However, despite the importance of this information, it is not being disseminated to other relevant stakeholders within the ecosystem. Therefore, the expert's suggestions include regular communication and distribution of this data to other concerned parties, which could be useful in facilitating better adaptation to the CE model and more effective waste management practices.

Regarding question 8 of the interviews, a significant number of participants indicated that they recorded carbon emissions and energy consumption data. However, it should be noted that this practice is still in its early stages across the entire construction industry. Furthermore, the data is currently recorded using centralized, manual methods such as Excel and SAP, which are unreliable for data recording. As a result, there are concerns about the data's accuracy and consistency. The accuracy of the accounts is not verified by any institution, but experts suggest that policymakers and government officials may introduce regulations in this area.

In summary, participants provided answers that supported and confirmed the barriers identified in the literature review. They emphasized that the most prominent barriers are the lack of a clear standard, lack of common awareness, and lack of material information dissemination. They also noted problems in recording energy consumption and CO_2 emission data.

The interviews also focused on understanding stakeholder relationships, the information they share, and how tracking, sharing, and preserving this information can contribute to circularity. As mentioned before, this study focuses on the process of constructing industrial steel. Therefore, question 9 in Table 6 was asked, and according to the responses received, an example flowchart is shown in Figure 15, which illustrates the stages of the industrial steel sector. First, the raw material supplier produces the raw material from iron ore or scrap metal. The raw material is then procured by an EPC firm to design, manufacture, supply, and construct the steel. Finally, once the raw material has reached the end of its useful life, the scrap metal is collected and recycled by waste recycling companies. In this cycle, the focus is on the collection of information from stakeholders that can have a positive impact on CE.

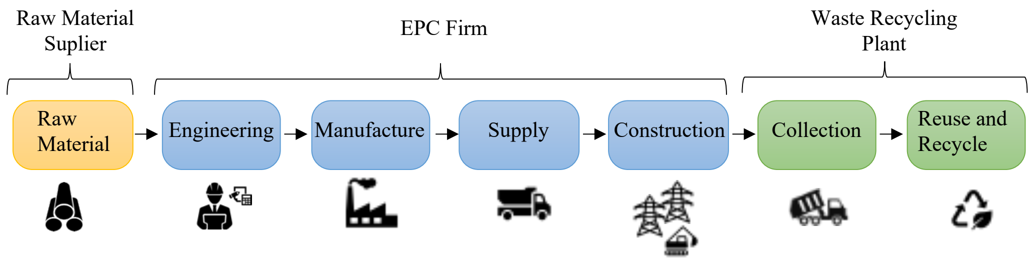

Figure 15. Flow Chart of Industrial Steel Construction

In conclusion, relationships between stakeholders were identified through interviews with builders, customers, suppliers, and recyclers. Information was gathered on industrial steel construction and the life cycle of steel. In addition, gaps were identified in information sharing, CE awareness and culture, material information sharing, energy consumption, and CO_2 emission records.

4.3 Result of the Assessment of Circular Economy Barriers

This section assesses CE issues derived from the literature review and supported by interviews with experts. The literature review showed that the construction sector faces several barriers to CE adoption, mainly lack of awareness, culture, traceability of material information, cooperation between stakeholders and lack of adequate standardization. The interviews with experts also revealed the lack of records on energy consumption and CO2 emissions. Often, stakeholders make records manually with software such as Excel worksheets, and this data is easy to change and lose. These drawbacks lead to preventing the adaptation of a CE. Therefore, traceability and transparency of the information flow between and within these stakeholders are essential to augment the transition to a CE and promote change in the culture of CE.

Consequently, four distinct barriers were identified. To address these challenges, the blockchain-based information flow framework is proposed. This solution provides transparent and secure information sharing, as well as efficient tracking and monitoring mechanisms for circular materials. The details of this framework are described in the next chapter.

CHAPTER 5

BLOCKCHAIN-BASED INFORMATION FLOW FRAMEWORK

Chapter 5 covers the framework's structure and includes an illustrative use case that demonstrates its potential. The chapter also discusses the framework's contributions and challenges and explains the validation process.

5.1 Structure of the Framework

The CE barriers assessed as a result of the literature review and expert interviews show the following results.

- Lack of awareness and culture
- No adequate standardization
- Lack of material information traceability
- Lack of records of energy consumption and CO_2 emissions

In this regard, the blockchain-based information flow framework is offered to eliminate these barriers. It is argued that by using this framework, all stakeholders in the construction industry can transfer beneficial information that can eliminate these shortcomings. Furthermore, the proposed framework is a guide for standardizing data sharing and promoting the circular economy.

During the development of this framework, a model structure was created to guide the process. As shown in Figure 16, participants in this structure can be raw material producers, construction companies, waste material factories and government authorities or policymakers. Assets are categorized as raw materials, construction materials and scrap. Shared transactions are energy consumption, CO_2 emission, material information, scrap percentage, waste percentage, location and date. This model structure can be customized according to the construction industry processes, materials and stakeholders to be implemented. In addition, the information on the construction material to be monitored can be added to the structure. This enables a thorough evaluation and confirmation of a material's environmental impact throughout its entire lifecycle. It also offers recycling opportunities for waste and scrap materials to the ecosystem.

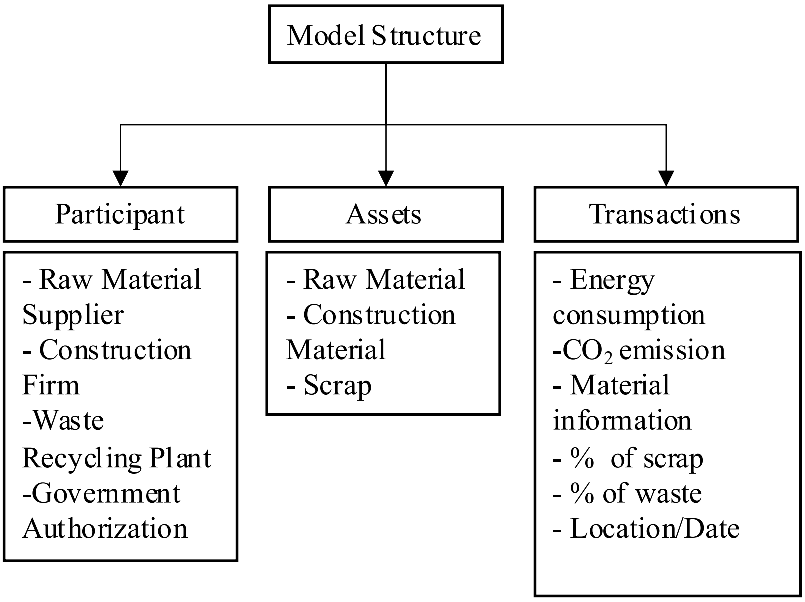

Figure 16. Model Structure of Framework

There are a number of considerations in constructing this framework. First, the accountability and transparency of the information transferred is vital for the entire ecosystem. Therefore, which blockchain structure should be used and whether there is a need for a distributed ledger structure was determined according to chart of Peck, (2017). Traditional databases store data centrally, which poses a threat to the reliability and security of the data. Therefore, in the designed framework, data should be stored in a distributed manner. In addition, all authorized users should update the current version of the data. In this way, users will not need to trust a third party. Stakeholders should be able to access helpful information that will increase circularity in the construction industry. Furthermore, predefined users with authorization can make changes to the data. Given these considerations, the use of a permissioned or consortium blockchain network, as illustrated in Figure 17, was deemed appropriate.

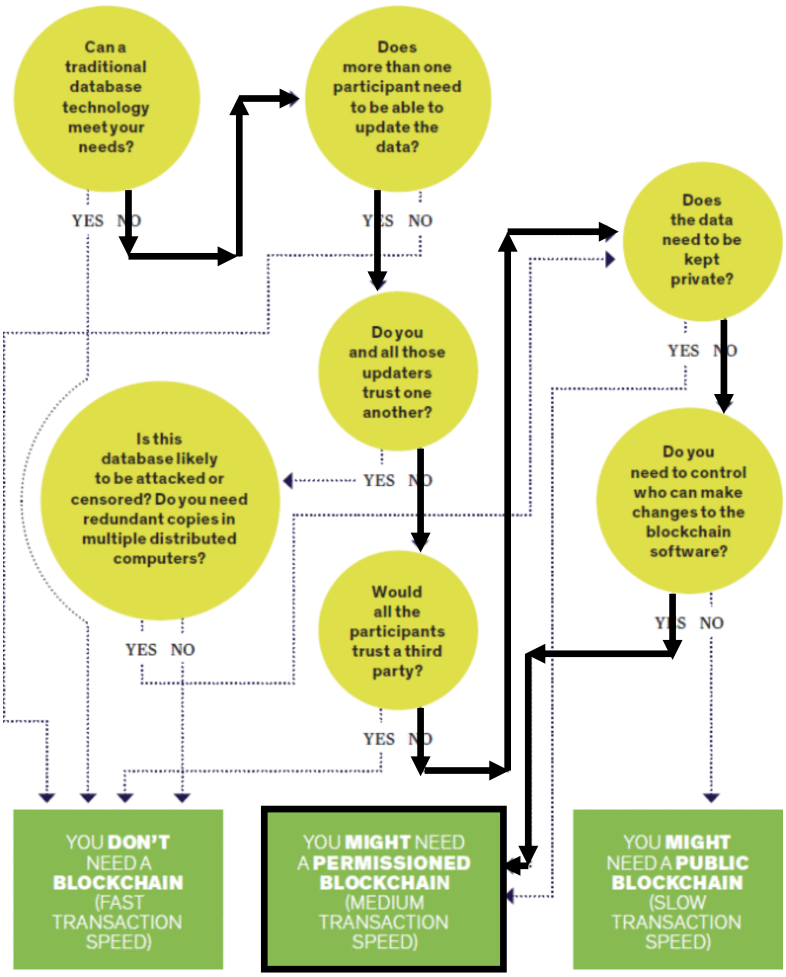

Figure 17. Blockchain Determination Chart (Peck, 2017)

Various platforms exist for building a consortium blockchain. Nonetheless, this study deemed Hyperledger Fabric to be the fitting choice for a blockchain platform. Hyperledger Fabric is the earliest and most commonly used among third-generation blockchain frameworks. Additionally, it is backed by IBM, has a robust community of supporters, and is user-friendly. One of the key features of the platform is its support for pluggable consensus protocols, allowing the platform to be customized more effectively for specific use cases and trust models. It is possible to easily specify consensus algorithms, nodes, peers and more.

Another important consideration is the process of collecting data. Manually transferring information into the system increases the likelihood of inaccuracies and can reduce trust. Thus, the utilization of emerging technologies such as IoT and sensors (RDIF) for data collection is planned. The framework takes into account the awareness of CE. It is crucial to ensure a user-friendly interface. In this way, stakeholders can integrate into the system more quickly, increasing utilization.

In construction projects, there is an intense flow of information between stakeholders, and it is important that this information is shared in a transparent and secure manner. The blockchain-based information flow framework emerges from the need to raise awareness of the CE, overcome inefficiencies, and increase the reliability and transparency of the material information flow in the construction industry. This framework considers suppliers, clients, construction companies, and recycling companies as participants in the construction processes, along with government authorities or policymakers who can provide incentives and standardization. Since the information flow framework is based on a consortium blockchain structure, unlike a public blockchain where users remain anonymous, a permission-based blockchain regulates the authorization of participants and transactions can be traced back to the actual participant. Participants in this consortium blockchain have different permissions. Figure 18 shows the example of predefined participants in the blockchain.

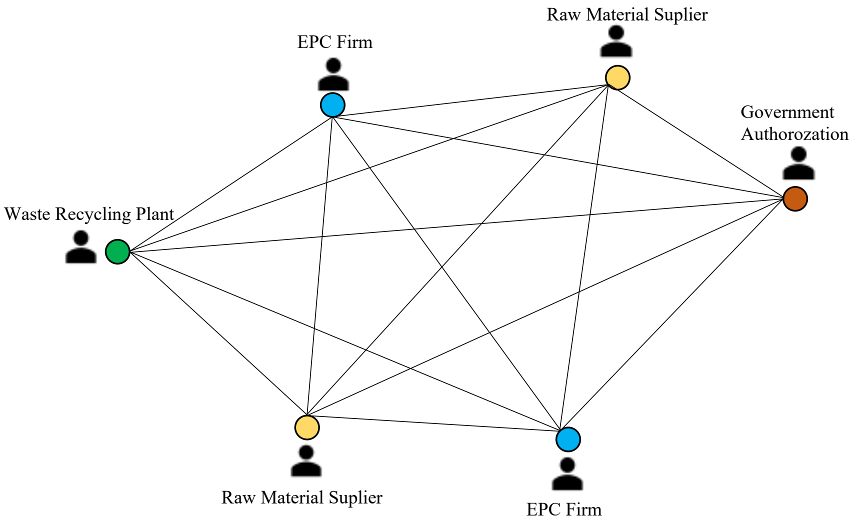

Figure 18. Participants in the Blockchain

5.2 Example Use Case in Industrial Steel Construction

The conceptual framework is exemplified through industrial steel construction. The participants are the raw material supplier, steel producer factory, steel supplier, construction steel manufacturer, contractor, recycling company, customer, and government authorities. The raw material producer, steel fabricator, steel supplier, construction steel producer, contractor, and recycling company have written and read authorization in the network, while policymakers and customers only have read authorization. As shown in Figure 19, the raw material supplier records the mine location and date, waste percentage, and energy and CO_2 consumption data in the mining operations process; the steel billet manufacturer factory, steel supplier, construction steel manufacturer, and contractor record the energy consumption & CO_2 emission, heat number of steel billets, scrap percentage, waste percentage and date, energy consumption, scrap percentage, the waste percentage in the production process; the recycling company records the energy consumption, amount of recycled material, location and date. The steel producer also records the percentage of steel billets produced from recycled steel.

Throughout the interviews, it was noted that the process of data collection and entry was performed manually. This can lead to errors and inaccuracies in the data, as well as a significant amount of time and effort being expended. To address these challenges, a new framework was presented that utilizes smart sensors and assistive technologies such as IoT to collect data in a more automated and efficient manner. By reducing the need for human intervention in the data collection process, the framework is able to improve its reliability and accuracy while also streamlining the workflow and reducing the risk of errors.

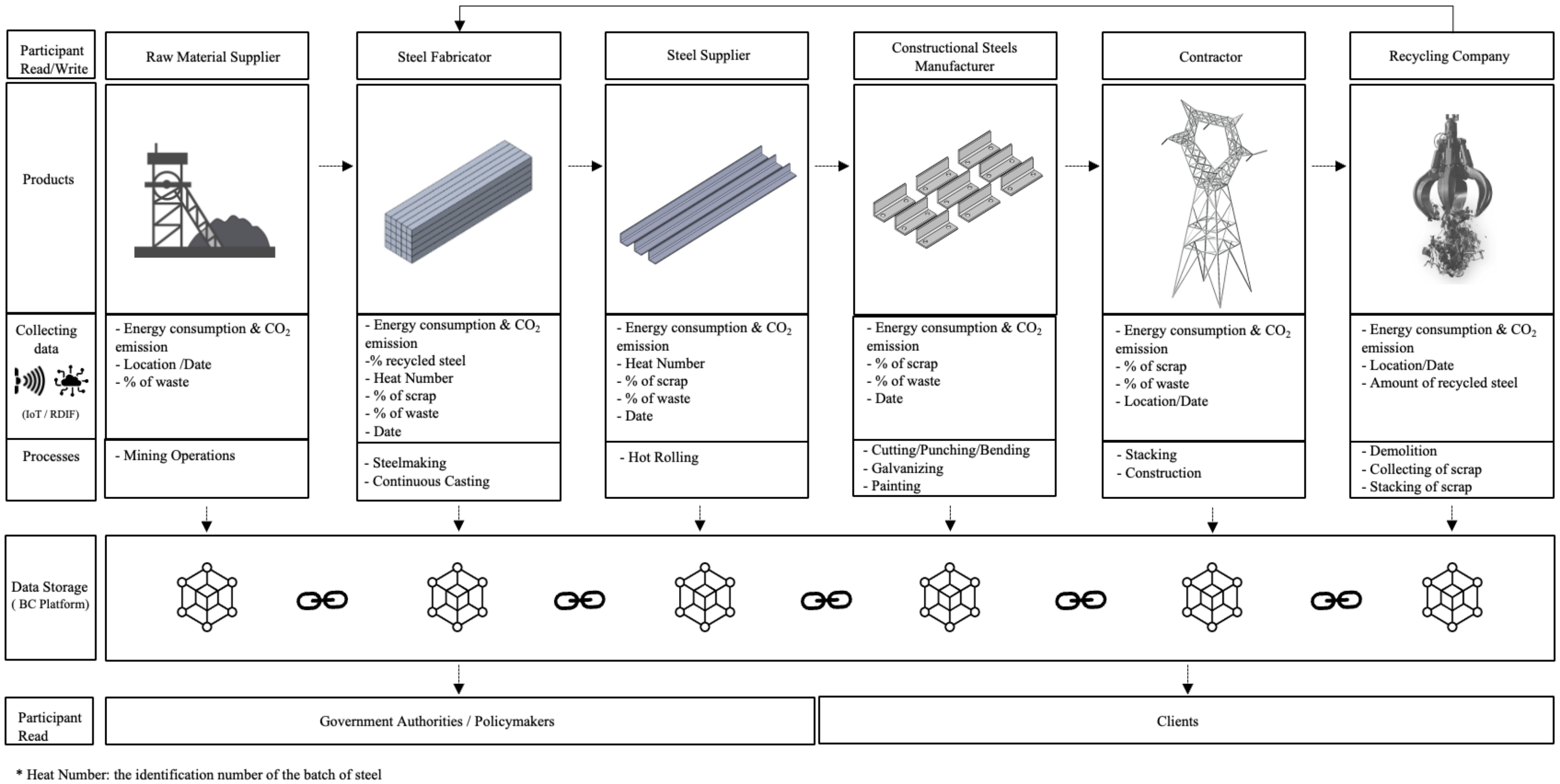

Figure 19. Example of Proposed Framework in Industrialized Steel Construction

An example from the steel construction industry is presented to provide a more comprehensive understanding of the framework. This serves to illustrate the finer details of the framework and the benefits it offers. Within this network, users have easy access to data that is crucial to the CE. For example, during expert interviews, it was noted that customers express a desire for recycled materials. To address this demand, our framework offers customers trustworthy and transparent details regarding the production process of the materials they purchase, including the percentage of recycled steel incorporated. Consequently, customers can make informed decisions and know precisely how much of the material they buy is recycled. Furthermore, the recycling company is able to make informed decisions about the recycling process by utilizing their knowledge of the amount of steel scrap that will be generated and the specific production methods that will be used. This allows them to plan strategically and evaluate the benefits of recycling in a more accurate and effective manner. The recycling company can optimize its operations to ensure maximum efficiency and sustainability by having this level of detail and insight into the process. In addition, one effective way for policymakers to encourage companies to adopt more sustainable practices is by closely monitoring their energy consumption and CO_2 emissions during steel production and manufacturing processes. By doing so, they can develop standardized guidelines and incentives that encourage firms to reduce their carbon footprint and adopt more environmentally friendly practices. Moreover, stakeholders can play a crucial role in promoting sustainability by monitoring the energy consumption and CO_2 emissions associated with the steel construction process. This can help identify areas where improvements can be made to enhance the sustainability of the construction process. For instance, stakeholders can examine the energy sources used for construction, assess the efficiency of the manufacturing processes, and determine the most effective ways to reduce waste and minimize environmental impact. Ultimately, such efforts can help promote a more sustainable future and CE culture for all. Also, one of the key benefits of having standardized data entry is that it can facilitate collaboration among users and foster the widespread adoption of CE. When working with standardized data, teams can easily share information and insights, compare performance metrics, and identify areas for improvement. This can help promote collaboration and drive a more holistic approach to problem-solving. Additionally, having a common framework for data entry can reduce errors and inconsistencies, ensuring that everyone is working from the same information and making decisions based on accurate data. Overall, standardization is essential to effective CE strategies and can help create a more engaged and collaborative culture within organizations.

This particular framework has been provided as an illustrative example to demonstrate the processes involved in carrying out specific tasks by an organization. It is important to note that in cases where an organization intends to implement this framework, it may need to be revised and adapted to meet its specific needs and conditions. Additionally, stakeholders' input and feedback should be considered, and any requests that may be useful for adapting the framework to the organization's specifics can be incorporated into the network. This will help ensure that the framework is customized to suit the organization's unique requirements and that it is able to deliver the desired results effectively and efficiently.

5.3 Validation of the Framework

This thesis presents a conceptual framework to address the challenges identified in CE adaptation and improve the construction sector's compliance with CE principles. To validate this approach, a case study was conducted in an EPC company. The framework was explained to experts, who were then asked to rate its competencies. The results indicate that it can be an effective enabler in the construction industry.

According to the results, the proposed framework has achieved a score of over 3,4 points in all categories. The evaluation ratings provided by the subject matter experts are documented in Table 8.

Table 8. Participant Ratings

Test	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Average Rate
Applicability	3	4	3	3	4	3,40
Record of CO_2 emission and energy consumption	4	4	4	5	4	4,20
CE awareness, culture, and collaboration	4	4	4	5	5	4,40
Standardization in the field of CE	3	4	4	4	3	3,60
Material Information Traceability	4	5	4	4	4	4,20

The applicability of the framework has been assessed by experts as beneficial for the sustainability of the entire construction ecosystem. They recommended that a real implementation be carried out to better understand and test the applicability of this framework. Graphical representations of participant ratings are given in Figures 20 and 21. As can be seen in these graphs, the highest average scores were given for the framework's enabling CE awareness, culture, and cooperation. On the other hand, the lowest score is for the applicability of the framework. In this context, it can be argued that the respondents have doubts about the applicability of this framework.

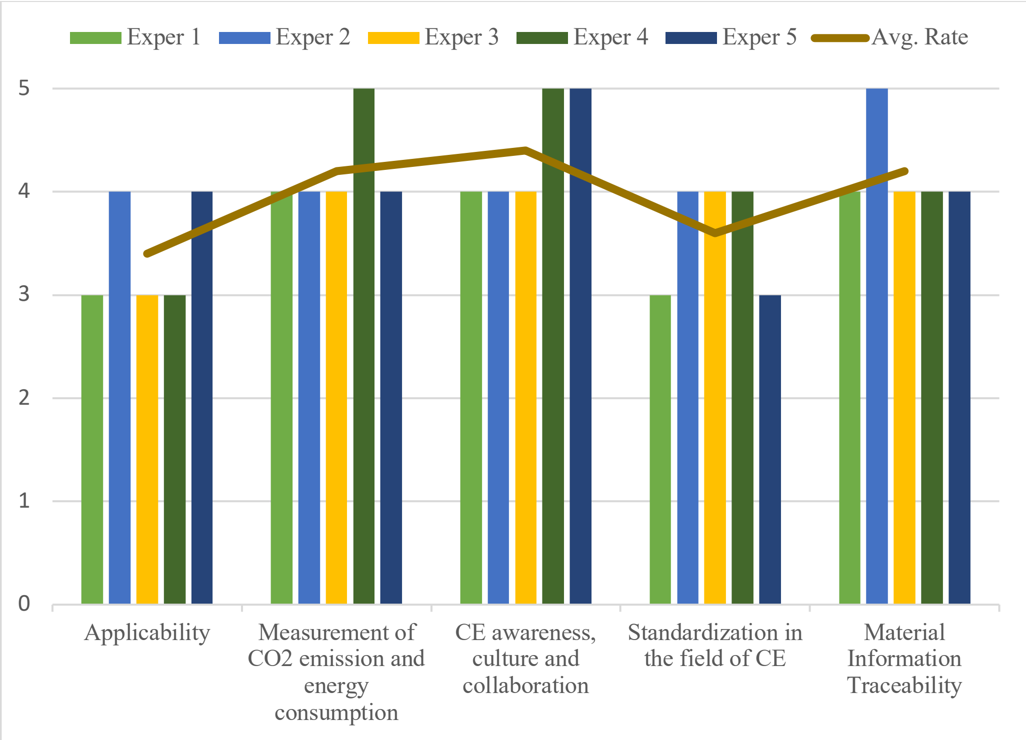

Figure 20.Participant Rating Graph - A

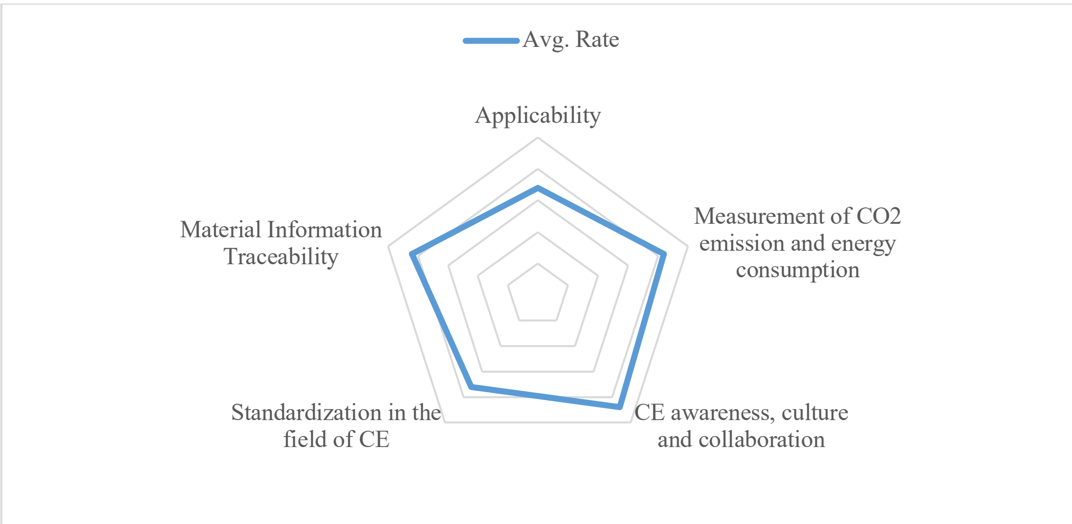

Figure 21. Participant Rating Graph - B

As a result, it was supported by the experts that the presented framework can accelerate and enhance CE adoption in the construction sector in many ways. Thus, the presented information flow framework was tested through the case study involving interviews with experts from the EPC company specializing in industrial steel construction.

5.4 Contributions and Benefits of the Proposed Framework

The presented framework is expected to contribute to the CE adaptation of the construction sector in different ways. These contributions are mainly related to energy consumption and CO_2 emission monitoring, CE awareness and culture, traceability of material information, waste and scrap management, regulation of incentives, and standardization. These contributions were tested through the case study. This section describes the contributions in detail.

5.4.1 Circular Economy Awareness and Culture

The mentioned framework serves as a comprehensive ecosystem that contributes to the smooth sharing of data and promotes a mindset and culture that encourages sustainable and circular practices. This cultural shift is essential for the long-term success of the construction industry as it involves integrating sustainability as a core value and behavior of all stakeholders in the construction supply chain. It requires a collective effort from all players in the industry, including contractors, clients, suppliers, manufacturers, and recyclers, to collaborate and implement sustainable practices at every stage of the construction process.

The framework can integrate CE awareness and culture into the decision-making processes of all participants. For instance, when planning a construction project, consider not only cost and timeline but also the environmental impact and circularity of materials. This integration ensures that CE principles become a core consideration in all strategic and operational decisions. It could also encourage collaborative problem-solving sessions among participants to address specific challenges related to CE practices. For instance, stakeholders can work together to explore innovative solutions if there are barriers to recycling construction materials. This approach fosters a culture of teamwork and shared responsibility for overcoming barriers to circular practices.

5.4.2 Energy Consumption and CO_2 Emission Monitoring

It was realized during the interviews that energy consumption and CO_2 emission are not well monitored and recorded during construction processes. This has a negative impact on CE awareness and possible sustainability solutions. This framework ensures the traceability and decentralized recording of this data. The energy consumption and CO_2 emission of each phase of construction can be monitored by all stakeholders. This information can be shared with other participants to collectively identify opportunities to reduce energy and CO_2 emission usage, such as adopting more energy-efficient equipment or practices. By promoting transparency and accountability, this approach can incentivize all stakeholders to prioritize energy efficiency and carbon reduction throughout the construction process. This helps achieve the overall goal of minimizing the environmental impact of construction industry.

5.4.3 Material Information Traceability

The lack of traceability of material information in the construction industry can pose significant challenges to achieving the CE, impeding the efficient implementation of closed-loop material cycles and the industry's overall sustainability. It becomes difficult to verify the suitability of materials for reuse or recycling without knowledge of their origin, composition, and history. The lack of confidence in recycled materials can discourage their use, perpetuating the depletion of natural resources and the associated environmental damage.

Additionally, recycled materials may be of mixed quality or even contaminated without proper traceability, leading to performance issues and safety concerns in new construction projects. However, the proposed framework allows participants to access origin and detailed information about construction materials. For instance, the supplier of raw materials can provide comprehensive information about the materials utilized in the construction process, such as their source and manufacturing techniques. This transparency enables all parties to verify that the materials meet sustainability standards and are responsibly sourced. Additionally, it facilitates tracking materials throughout their lifecycle, promoting accountability and responsible sourcing.

5.4.4 Waste and Scrap Management

Adopting the CE approach to waste and scrap management in the construction industry is essential for long-term sustainability. This involves moving beyond the traditional 'take-make-dispose' model and instead viewing construction as a system where resources are reused and recycled. Scrap and waste are generated at many stages of the construction process. Managing them effectively is essential to contribute to the CE. In the presented framework, all participants record data related to waste and scrap generation and distribute it to all stakeholders. Stakeholders who produce scrap can provide real-time data on the scrap percentage generated during construction. This information can help identify areas where waste can be minimized and encourage the adoption of practices that reduce material waste. The waste recycler can promote CE by reusing materials that would otherwise be discarded and can use this data to plan and optimize recycling processes.

5.4.5 Standardization and Incentives

The proposed framework for measuring sustainability metrics is a valuable tool for policymakers and government officials. It allows them to incentivize or penalize construction companies based on their sustainability performance. For instance, a company that consistently reduces energy consumption and waste production may receive incentives, while those that fail to meet sustainability targets may face penalties. This approach encourages all participants to actively contribute to sustainable and circular practices. The data generated by this framework is also useful for standardization purposes. Policymakers can use it to develop and implement future construction standards that aim to reduce environmental impact. With this framework, monitoring and regulating the quality of data, production standards, energy consumption, and CO_2 emissions of processes becomes more feasible. Overall, this framework serves as a comprehensive tool that can assist in promoting sustainable practices, reduce environmental impact, and encourage all stakeholders to prioritize sustainability in their operations.

5.5 Challenges of Implementing the Framework

It is anticipated that there may be financial, cultural, and technological challenges in implementing this framework. The presented conceptual blockchain-based information flow framework may not be financially feasible for small construction companies. For them, investing in this framework may not be a priority. Government incentives may be needed to develop a more cost-effective solution that is also accessible to them. On the other hand, the conservative nature of the construction industry and the lack of CE culture are cultural limitations that hinder the implementation of this framework. It can be difficult for the construction industry to adapt to new technologies, making a rapid transition to this framework difficult. Fostering a more collaborative and innovative working environment for the construction industry could encourage the adoption of new technologies.

CHAPTER 6

CONCLUSION

The final chapter provides a brief summary of the thesis, the limitations that were encountered in the conduct of this study, and recommendations for future research.

6.1 Summary

The circular economy (CE) is an economic model that prioritizes reducing waste and optimizing resource efficiency. It seeks to extend the life of products and materials by promoting recycling, reuse, and other sustainable strategies. The transition to CE is seen as critical for many industries to achieve long-term sustainability goals. However, the literature review and expert opinions confirm that there are many barriers to the transition from the traditional linear economy to the CE in the construction sector. This study focuses on the lack of awareness and culture, adequate standardization, material information traceability, and records of energy consumption and CO_2 emissions. To overcome these barriers, a conceptual blockchain-based information flow framework has been developed.

In summary, the presented blockchain-based framework provides a foundation for decision-making and innovation to support environmentally responsible construction processes by promoting transparency, material tracking, accountability, and collaboration among participants. The framework creates an ecosystem where stakeholders work collectively for sustainable and circular practices in the construction industry. These contributions and benefits are tested through the case study. The case study was conducted in a large EPC company operating in the field of industrial steel construction. Experienced employees in this company have explained the framework and asked to evaluate it by ratings. At the end of this study, it was concluded that the framework was an effective enabler for overcoming the identified barriers.

6.2 Limitations

There are several limitations to this study. The main ones are that the framework was tested for a single construction company, the results depend on the experience and knowledge of the experts, there is a lack of real applications for the use of sensors, and there is a transparency issue for the consortium blockchain.

This framework has been tested in discussions with a large industrial steel construction company, but this is not enough to come to a definitive conclusion. This framework needs to be tested in more and different construction sites. In addition, the lack of knowledge of the experts interviewed may reduce the quality of the data collected. Contributions from participants with insufficient experience and knowledge may not be considered appropriate. On the other hand, the study suggests that data can be collected with the help of sensors, but it is difficult to find real applications in this field. The lack of an efficient implementation of this system is an example of the limitations of this study. Finally, the consortium blockchain has limited transparency. It has a limited number of nodes, which makes it vulnerable to security threats. Therefore, the selection of participants in the establishment of this blockchain network should be done carefully.

6.3 Recommendations for Future Studies

As stated in the study, the framework was developed conceptually. It is expected that this framework will be utilized in real-world construction industry applications in future studies. Furthermore, the study only tested the framework with a case study on industrial steel construction. It would be beneficial to test the framework with various materials and transactions in multiple construction sectors. In more advanced work, incentives and penalties could be based on specific criteria and automated with smart contracts. It is also possible to add new users in future work. For instance, this framework can function as a trusted and immutable database for academics to join and use in their research. Although this is a consortium blockchain, it may be necessary to keep some information confidential. Therefore, zero-knowledge proofs (ZKP) can be used to enhance privacy. Finally, the framework can be organized and used to provide a reliable solution for collecting data in LCA.

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