sustainability

MDPI

Article

Blockchain-Enabled Construction and Demolition Waste Management: Advancing Information Management for Enhanced Sustainability and Efficiency

Xiaozhi Ma, Hongping Yuan * and Wenbo Du

School of Management, Guangzhou University, Guangzhou 523000, China; xiaozhi.ma@gzhu.edu.cn (X.M.); wbdu@e.gzhu.edu.cn (W.D.)
* Correspondence: hpyuan@gzhu.edu.cn

Abstract: The construction industry is a significant contributor to global carbon emissions, primarily due to the generation of substantial construction and demolition waste. However, the current practices in construction and demolition waste management (CDWM) face various information management challenges that undermine their overall effectiveness. Correspondingly, this research proposes the integration of blockchain technology as a strategic solution to enhance the efficiency and effectiveness of CDWM. Despite the potential of blockchain in revolutionizing CDWM, research in this area remains limited. To address such a gap, this study adopts a design science action research methodology to integrate the use of blockchain technology into CDWM. Specifically, this study has creatively introduced the blockchain-based data supply chain to address the principal–agent problem in CDWM and develop a novel blockchain-enabled framework for CDWM. Additionally, a six-layer system architecture for the blockchain-based CDWM information system has been developed. This integration holds the promise of streamlining and empowering CDWM processes and thereby improving the administration and regulation of CDWM. Notably, the utilization of blockchain technology also presents an innovative opportunity for carbon reduction and offsetting within the construction industry. This research makes a substantial contribution to the field by introducing a novel approach to address information management challenges in CDWM, thereby promoting sustainable practices in the construction industry.

Keywords: construction and demolition waste management (CDWM); illegal waste dumping; blockchain; information management; sustainable development

check for updates

Citation: Ma, X.; Yuan, H.; Du, W. Blockchain-Enabled Construction and Demolition Waste Management: Advancing Information Management for Enhanced Sustainability and Efficiency. *Sustainability* **2024**, *16*, 721. https://doi.org/10.3390/su16020721

Academic Editors: Antonio Caggiano, Zezhou Wu, Zhikun Ding, Huabo Duan and Jiayuan Wang

Received: 1 December 2023
Revised: 11 January 2024
Accepted: 12 January 2024
Published: 14 January 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The construction industry plays a vital role in the sustainable development of human society by producing buildings, facilities, and infrastructures. However, this industry inevitably generates a substantial volume of construction and demolition waste (CDW), thereby posing a significant global challenge in waste management [1]. This challenge is amplified by the increasing scale of urban development and the consequent rise in CDW. It is essential for the construction industry to address this issue in order to achieve sustainability and contribute to the United Nations' Sustainable Development Goals (UNSDGs) [2].

Construction and demolition waste management (CDWM) is crucial to the construction industry for reducing carbon emissions through various strategies, including minimizing waste generation, optimizing material use, promoting energy-efficient practices, and embracing a circular economy model [3,4]. CDWM is also key to the sustainability performance of the construction industry in terms of environmental protection and clean production [1]. Despite these benefits, the current CDWM framework encounters significant challenges, which are primarily due to ineffective information systems and inadequate administration, thus leading to inconsistent reporting and data collection, which lead to ineffective CDWM [5,6]. These challenges not only hamper the effectiveness of CDWM but also impede the realization of the UNSDGs.

The integration of blockchain technology into CDWM offers a promising opportunity to address the prevalent issues in this field, particularly by enhancing the traceability and reliability of information [7]. The blockchain's inherent characteristics, such as creating tamper-proof and immutable records, can significantly reduce data manipulation, thereby improving the tracking and supervision of waste generation in CDWM processes [8]. As a technical infrastructure for the CDWM information system (CDWMIS), the blockchain can simplify waste management processes by reducing the reliance on intermediaries and extensive paperwork [9]. This study focuses specifically on the CDWMIS, thereby exploring the potential of the blockchain to enhance these systems. Given the limited attention this approach has received in international research, the primary objective of this study is to propose a blockchain-based framework and solutions to improve the CDWMIS. This research aims to contribute to the field by addressing a significant gap in the current academic discourse and offering innovative pathways for more efficient waste management within the construction industry.

This paper is structured into six sections. After the introduction section (Section 1), Section 2 conducts a literature review to identify the theoretical foundation and research gap. Section 3 outlines the design science action research methodology employed in this study. Section 4 presents the findings obtained through the analysis. The contributions, as well as the potential and critical analysis to improve the CDWMIS using blockchain technology, are discussed in Section 5. Finally, Section 6 concludes the findings, highlights the limitations of the study, and suggests future research. The main contribution of this study is to design a blockchain-enabled CDWMIS to enhance the efficiency of CDWM by integrating theories and blockchain technology into CDWM practices in order to facilitate more sustainable construction.

2. Literature Review

2.1. Information Management in CDW Management and Administration

Effective information management is paramount to the management and administration of CDW. Primarily, the effective handling of waste information facilitates the appropriate sorting of waste that guides to the most suitable management strategies [5]. This process is crucial, as it enables the tracking of waste generation and disposal, thereby ensuring accountability among waste generators and aiding stakeholders in monitoring their waste practices. Additionally, efficient information management aids in identifying optimal waste disposal methods and in the judicious allocation of resources to minimize waste generation [6]. Furthermore, monitoring CDW during its transportation is vital for adhering to regulatory standards and ensuring proper waste handling [10].

The review of existing literature finds a diverse range of technical solutions for CDW information management. For instance, studies by Aslam et al. [11] and Li et al. [12] emphasize the role of global positioning systems in enhancing waste management information systems. Wang et al. [9] introduced a municipal waste management system utilizing smartphone and computer applications to track illegal waste disposal. Cao and Ding [13] proposed an integrated approach combining computer simulation and geographic information systems for managing the transportation of municipal CDW. Additionally, Xu et al. [14] and Jalaei et al. [10] advocate the use of building information modeling (BIM) for CDW information management.

2.2. The Application of Blockchain in the Construction Industry and CDW Information Management

The blockchain has a wide range of applications in the construction industry according to existing research. One major application is to integrate blockchain technology with other digital twin technologies, e.g., BIM and the Internet of Things e.g., [15–17], to enable more efficient information management in construction. Blockchain technology is also associated with modular construction to facilitate automatic information management e.g., [18–20]. Moreover, a few studies, such as Siountri et al. [15] and Götz et al. [21], contribute to expanding the use of blockchain technology in asset management. Notably, several studies, such as Figueiredo et al. [22] and Shojaei [23], are found to link blockchain use with sustainable construction.

It is no exception to CDWM. A further examination of the literature reveals a steady advancement in the application of blockchain technology to CDWM. Two earlier study published in 2020, Perera et al. [24] and França et al. [25], highlighted the potential of blockchain technology in enhancing construction waste information systems, thereby laying the groundwork for further exploration in this area. Scott et al. [7] identified this integration as a new and promising research opportunity. In a more specific application, Wu et al. [26] concentrated on resolving technical challenges associated with utilizing the blockchain for tracing and verifying construction waste information.

2.3. Research Gap in Blockchain-Enabled CDWM

Despite the research progress mentioned above, there is still a significant research gap to systematically integrate blockchain technology into CDWM. This gap is particularly evident in exploring how the blockchain can be leveraged to revolutionize the information management aspect of CDW. Thus, this research introduces a novel approach by integrating blockchain technology into CDWM. The primary objective of this study is to address this research gap by proposing a comprehensive solution based on blockchain technology for the CDWMIS. By doing so, it seeks to enhance the efficiency, reliability, and transparency of CDWM, thereby providing a unique and valuable contribution to the existing body of knowledge.

3. Research Method

This study employed a design science action research approach to develop the blockchain-enabled CDWM framework and the system architecture of the information system. To implement the study, researchers collaborated with specialists from a consulting company with their business focusing on the implementation of digital technologies in various industries. Via the design science action research approach, this study benefited from the different expertise of the researchers and practitioners to integrate theory into practice and introduce blockchain technology into CDWM and its information systems. The details of the research approach are introduced as follows.

3.1. The Design Science Action Research

This study adopted design science action research, which is a method widely recognized for its effectiveness in management and information systems research, particularly due to its systematic and rigorous approach [27]. Design science is instrumental in fostering practical solutions and technological advancements, thereby allowing for the investigation of information systems across various business processes, even in the absence of a specific case study [28]. According to Peffers et al. [29], the design science methodology encompasses several steps: (1) identifying the problem; (2) defining objectives; (3) designing artefacts and developing solutions; (4) demonstration and evaluation; (5) reflection and iteration; and (6) communication of the research. Notably, the iterative cycle of Steps 3, 4, and 5 aligns with action research, as exemplified by Hartmann et al. [28]. This iterative process is crucial to this study, where researchers and practitioners collaboratively developed and refined blockchain-based systems and solutions for the CDWMIS. Data collection in this study involved participative observation, interviews, document analysis, and focus group discussion, thereby allowing for a comprehensive understanding of the practical applications and challenges in implementing blockchain in the CDWMIS. These qualitative data collection methods provided valuable insights into the system's functionality and user interaction, which were integral to the research process. The specific research approach adopted in this study is illustrated in Figure 1, which details the integration of design science and action research in developing and evaluating the blockchain-based solutions for the CDWMIS.

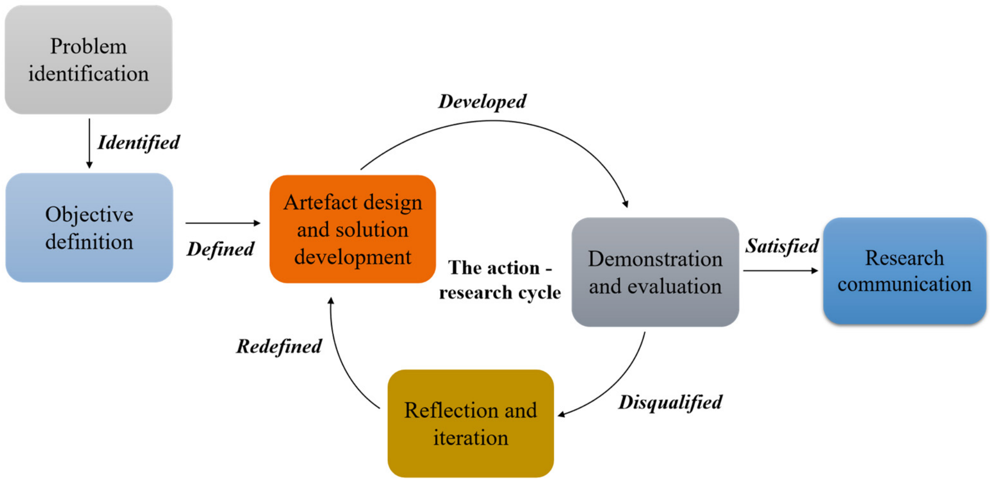

Figure 1. The design science action research process of this study.

3.2. *The Implementation of the Design Science Action Research*

The implementation of this study adhered to the design science action research process, as depicted in Figure 1. This section elaborates on the process and begins with problem identification.

3.2.1. Problem Identification

The main problem in CDW information management that blockchain technology seeks to solve is the presence of information asymmetry, together with the difficulty of collaborative information management. This study employed two theoretical frameworks to analyze these challenges, namely, the principal–agent theory and the data supply chain theory.

The Principal–Agent Theory: Originating from the work by Spremann [30], the principal–agent theory or problem describes potential conflicts of interest between an agent and a principal in delegated work efforts, which is a prevalent scenario in business and political settings. This issue is particularly relevant to CDWM, as evidenced by Sezer and Bosch-Sijtsema [31], who highlighted the various connections and conflicts of interest in CDW information management. Blockchain technology can mitigate these issues by encrypting critical information and documenting changes, thereby safeguarding communication and information sharing among CDWM actors.

Data Supply Chain: This concept, as discussed by Akinade et al. [32], refers to the collaborative relationships formed among various actors involved in data exchange activities and information management. In the context of CDWM, the data supply chain necessitates collaboration among diverse stakeholders. Blockchain technology can enhance this aspect by providing cybersecurity, transparency, and trust-free mechanisms.

Consequently, this study has proposed blockchain-based solutions to address the principal–agent problem and enhance the data supply chain in CDW information management and data exchange.

3.2.2. Objective Definition

In this study, the primary aim was to leverage blockchain technology to enhance CDW information management, which would be guided by the principles of the principal–agent and data supply chain theories. This overarching objective was divided into two specific goals:

(1) *Identification and Encryption of Critical Information:* Utilizing the blockchain's robust encryption capabilities, this study aimed to identify and secure critical data in CDWM.

This could enhance both transparency and security in data and information sharing, thereby addressing the principal–agent conflicts by mitigating the risks of information manipulation and mismanagement.

(2) *Establishment of a Blockchain-Enhanced Data Supply Framework:* The second objective was to develop a blockchain-based framework that facilitates collaborative working and effective supervision within CDW information management. This framework could leverage blockchain's inherent features, such as decentralized ledgers and smart contracts, to promote a more integrated and efficient data supply chain, thereby enhancing collaboration and oversight across different CDWM stakeholders.

3.2.3. Artefact Design and Solution Development

In this phase, a blockchain-based data supply chain was identified and designed as the primary artefact to enhance CDW information management (Figure 2). This artefact aligned with the objectives to address the principal–agent problem and improve the data supply chain using blockchain technology. The supply of data through blocks formed a chain to address the principal–agent problem. The operational actors can be either agent or principal in different scenarios, but the information gap can be fulfilled by the blockchain-enabled transparency. To address this, it is necessary to develop a comprehensive framework for data supply that incorporates blockchain technology and an application architecture. These components form the central outputs of the design process.

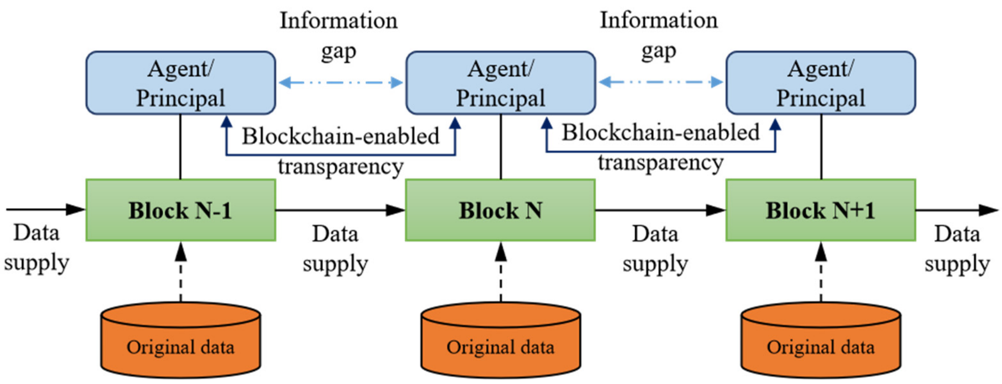

Figure 2. A design of blockchain-based data supply chain to address the principal–agent problem.

3.2.4. Demonstration and Evaluation

The demonstration and evaluation of the designed artefact were conducted through a focus group discussion involving researchers and two practitioner experts specializing in blockchain implementation and CDWM. This collaborative approach allowed for a thorough validation of the blockchain-based solutions and an assessment of their practical impact and effectiveness in the field.

3.2.5. Reflection and Iteration

The post-evaluation engaged in a reflective process to analyze the results and identify areas for improvement. This reflection, coupled with subsequent iterations of the artefact design and solution development, formed an iterative cycle aimed at refining and enhancing the design to better meet the objectives.

3.2.6. Research Communication

The final stage involved communicating the research findings to both industry practitioners and the academic community. Engaging with industry practitioners aided in the practical application and advancement of CDWM practices and CDW information management. Simultaneously, the examination of findings in the existing research contributed to identifying the critical problems that hindered the effective implementation of CDW information management and developing new pathways for the further improvement of the CDWMIS with blockchain technology.

3.3. Addressing Research Method Limits

The typical limit of design science is the validation of the design. This study employed action research to address such a limit, as the iterative improvement through the interactions of researcher and practitioners can mitigate the design deviation [33]. Moreover, the structural research approach, as illustrated in Figure 1, was followed to enhance the validity of the design science action research approach.

4. The Blockchain-Enabled CDWM Framework and the System Architecture of the Information System

4.1. Primary Principles of Blockchain-Enabled Information Tracking for CDWM

Through constant collaborations with practitioners in the action research phase, this study has identified key principles that underpin the effectiveness of blockchain-based solutions in CDWM.

4.1.1. Data Supply Chain for CDWM

The CDWM process encompasses several stages, including waste generation, processing (such as quantification, reduction, reuse, and trading), transportation, and disposal (recycling or dumping). Notably, in the context of CDWM, crucial information data include information on on-site waste generation, waste transactions, transportation, and disposal methods. This collaborative effort forms a chain of interconnected actors, with each playing a role in the CDW management process. By conceptualizing this information as a 'material' in a data supply chain, as illustrated in Figure 3, the flow of information in CDWM can be better understood and managed. A key principle in this context is the formation of a closed-loop data supply chain, where information is consistently and transparently shared among all actors, thereby ensuring consensus and accuracy in data management.

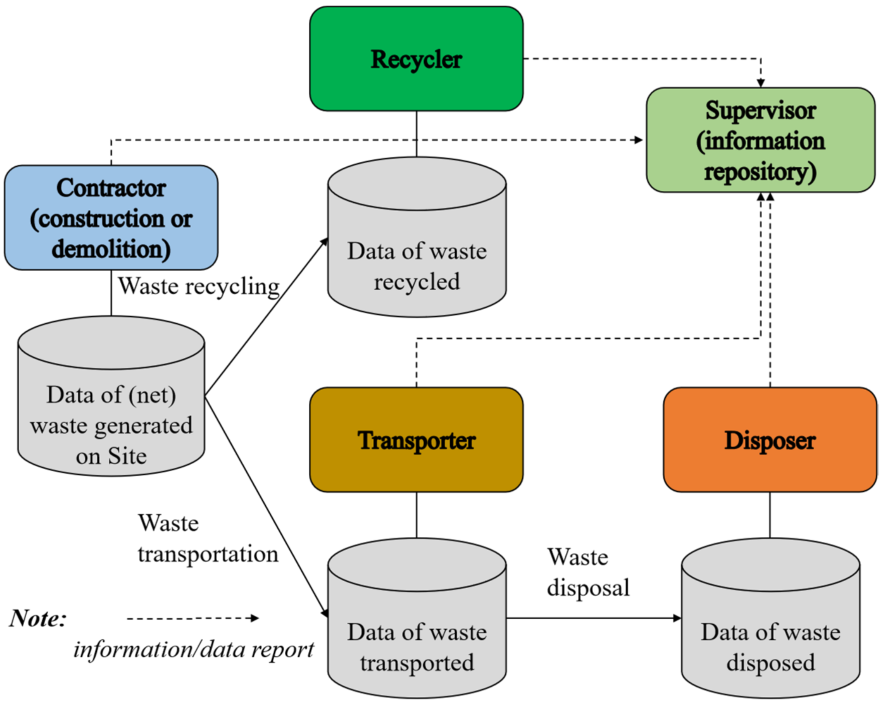

Figure 3. CDWM data supply chain.

Several findings related to the specifics of CDWM data supply and information management were captured. The categorization of CDWM information and data concerning different actors in the process are outlined in Table 1. Additionally, Table 2 lists the challenges in CDW information management that blockchain technology has the potential to address. These tables provide a comprehensive overview of the current state of CDW information management and the areas where blockchain technology can improve.

Table 1. CDWM information and data for different actors.

Actor	Category of CDWM Information and Data
Contractor	CDW generation quantity, time, person in charge, CDW material type, building or work-related information, etc.
Transporter	Vehicle and transportation quantity, time, person in charge, transportation trail, end space, etc.
Recycler	Received quantity, time, person in charge, CDW handling information, etc.
Disposer	Received quantity, time, person in charge, disposal site information, CDW disposal information, etc.

Table 2. CDW information management issues and relevant blockchain's function/feature.

CDW Information Management Issues	Blockchain's Function/Feature	References
Distorted information or data security	Information encryption	[7,24,26]
Lack of transparency	Distributed ledger	[7,8,34]
Miscellaneous checking procedures	Smart contract	[35,36]

4.1.2. Main Functions to Employ Blockchain-Enhanced Data Supply Chain in the CDWM Context

To effectively implement the design, it is crucial to understand and clarify several main blockchain functions that are instrumental in enhancing the data supply chain within the CDWM context:

Data on Chain: This process involves uploading identified critical data to the blockchain-enhanced data supply chain, thereby linking the data with the responsible actors in the CDWM process.

Consensus Mechanism: This mechanism employs digital agreements as a means of authorization, thus functioning as consensus nodes in CDWM to validate and protect data.

Auditing: Set by administrators, this function involves the establishment of rules and regulations for monitoring and auditing data on the blockchain, including provisions for addressing non-compliance.

Supervision: This aspect focuses on addressing misbehaviors in CDW management by assigning specific responsibilities to individuals or delegates from authoritative bodies.

4.1.3. Blockchain-Enhanced CDWM Framework

Drawing from the above analysis, a blockchain-enhanced CDWM framework was developed, as depicted in Figure 4. The framework encompasses several procedures: Firstly, an authorization mechanism is established to select authorization nodes within the CDWM actor alliance, which is based on previously achieved consensus and digital agreements. Subsequently, CDW information and data from different nodes are uploaded onto the blockchain. Finally, supervisors access CDW disposal information from the blockchain and provide feedback to verify and validate the information. This framework aims to streamline the CDWM process, thus enhancing transparency, accountability, and efficiency through the strategic application of blockchain technology.

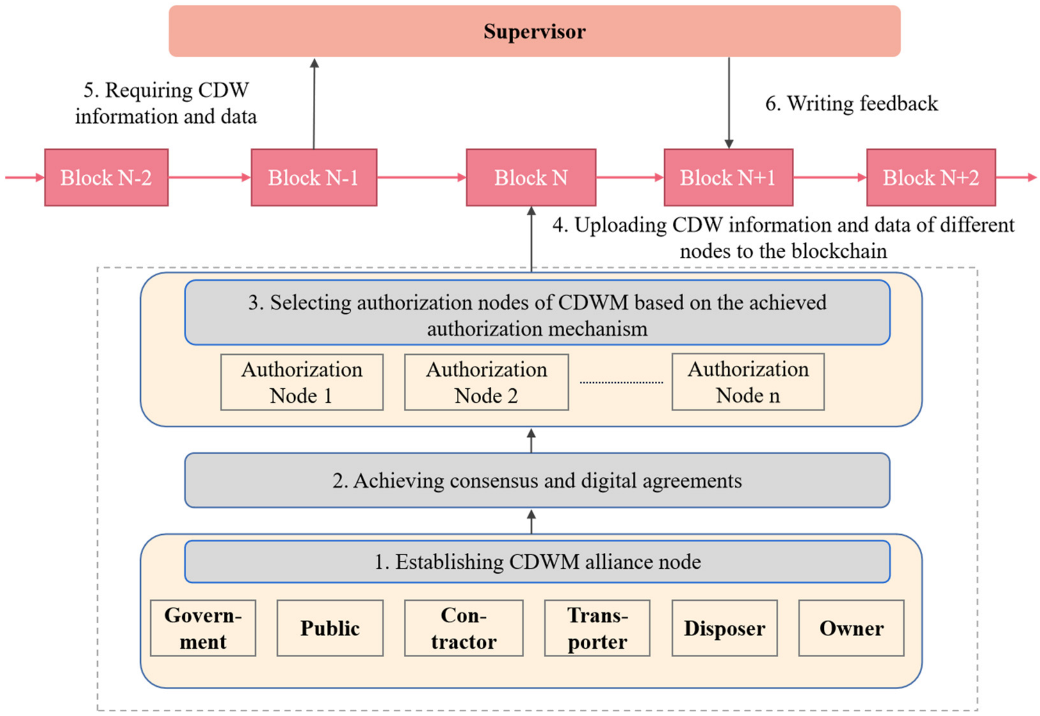

Figure 4. Blockchain-enhanced CDWM framework.

4.2. Integrating Blockchain into CDWM Information System

4.2.1. Organizational Structure

The organizational structure of CDWM, as illustrated in Figure 5, plays a critical role in understanding the dynamics of waste management processes. In this structure, the administration group, typically comprising the principal supervisor (usually the building and construction administrative body) and co-supervisors (such as the transportation, environment, and municipal administrative bodies), along with the public, can supervise and interact with the various CDWM actors. A common issue in this structure is the principal–agent problem, where conflicts of interest may arise between these administrative bodies and other CDWM actors.

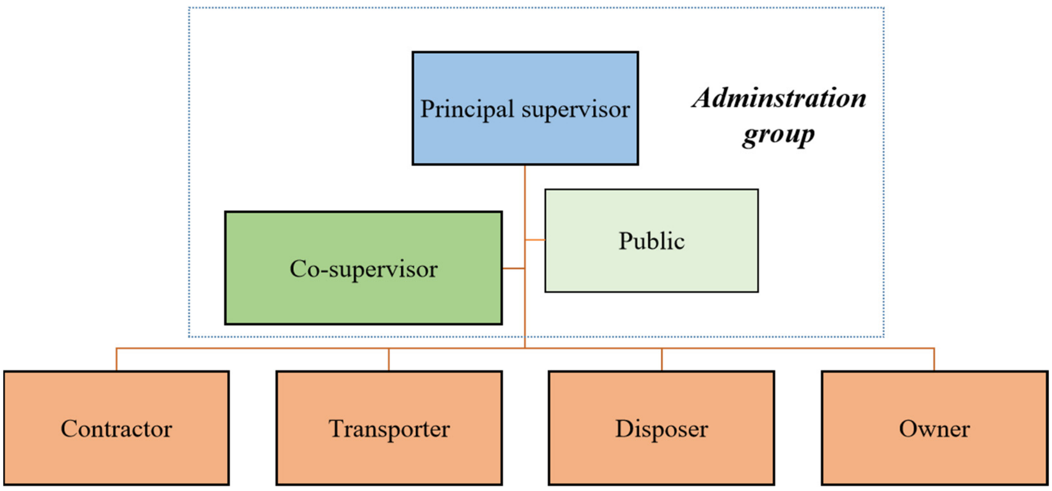

Figure 5. The organizational structure of CDWM.

Traditional practices in CDW information management encounter limitations, which become particularly evident in situations of illegal CDW dumping. These practices often struggle to adequately address conflicts of interest and enforce regulations effectively. The introduction of blockchain technology into the CDWM information system presents a novel approach to overcoming these challenges. Blockchain's capabilities, such as its decentralized nature, transparency, and secure data management, offer significant advantages in managing the complexities and conflicts within CDWM organizational structures. By leveraging blockchain technology, this study can enhance accountability and improve the monitoring and regulation of CDW practices, thereby addressing issues, like illegal dumping, more effectively.

4.2.2. System Architecture

Figure 6 demonstrates the comprehensive system architecture of the blockchain-enhanced CDWMIS, thereby comprising six distinct layers: the application layer, user layer, blockchain platform layer, supportive service layer, blockchain API and SDK layer, and blockchain-as-a-service (Baas) infrastructure layer. The Baas infrastructure layer is the foundational layer responsible for collecting, processing, storing, and encrypting critical CDW information and data, thereby forming the base of the CDWM information system. The two layers of the blockchain API and SDK layer and the supportive service layer work in conjunction to enable the encryption and secure handling of information and data using blockchain technology. At the blockchain platform layer, the encrypted information and data are disseminated across the alliance network, thereby leveraging the decentralized and secure features of blockchain technology. The user layer accommodates various actors in the CDWM process, including contractors, transporters, disposers, owners, supervisors, and the public. These actors have access to the blockchain-based CDWM information system to search, verify, and check CDW information and data. Serving as the interface, the application layer processes the information and data retrieved from the preceding layers and provides application services tailored to the needs of the CDWM process. This layered architecture effectively realizes the implementation of the blockchain-enhanced CDWM information system. It showcases how blockchain technology can be integrated at various levels to enhance the security, transparency, and efficiency of CDW information management, as visually represented in Figure 6.

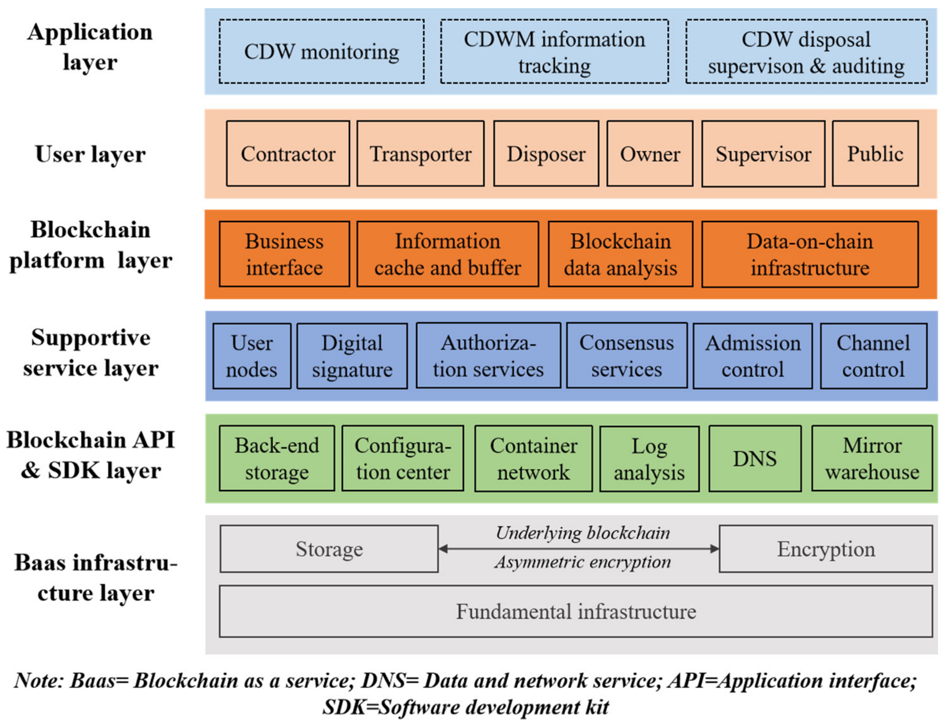

Figure 6. The system architecture of the blockchain-enhanced CDWM information system.

4.3. Major Impacts and Potential Problems of the Blockchain-Enhanced CDWM Information System

A focus group discussion involving researcher and practical specialists was held to post-evaluate the system design and provide reflections. The effects and potential challenges of the blockchain-enhanced CDWM information system, as identified by the focus group discussion, are outlined below.

4.3.1. Major Impacts

The incorporation of blockchain technology can significantly improve both CDW information management and the overall CDWM process. At the CDW information management level, blockchain's encryption capabilities ensure the security and privacy of data. Additionally, the inherent tamper-proof nature of blockchain technology fosters transparency across CDWM practices, administration, and supervision. In large-scale CDWM operations, the use of smart contracts can streamline repeated checking procedures, although standardizing these applications for some irregular CDWM tasks remains challenging. Overall, these impacts contribute to enhancing the effectiveness and digitalization of CDWM, as well as improving the administrative and regulatory systems within the sector.

4.3.2. Potential Problems

Several potential issues could affect the efficiency and effectiveness of the system. Technical challenges, particularly related to data sharing and storage, are of primary concern. Additionally, ensuring that personnel are adequately trained and capable of operating the new information system poses a significant challenge. The development and support of regulatory frameworks, along with governmental backing, are also crucial to the broader adoption of the system. While technical problems need to be addressed during system development, other issues, such as training and regulatory support, require comprehensive managerial strategies.

5. Discussion

5.1. Contributions

This study adopts the organizational perspective, especially the principal–agent theory and data supply chain theory, to leverage the blockchain's impact on CDWM. The integration of blockchain technology into CDWM presents significant theoretical potential and practical potential, which are discussed in detail below.

5.1.1. Theoretical Contributions

This study enhances the theoretical foundation of CDWM, particularly in the realm of CDW information management, by identifying key issues related to the principal–agent problem and introducing the concept of the data supply chain. The application of blockchain technology provides a nuanced interpretation of these theories, specifically in the context of CDWM. This study takes a novel approach by adopting an organizational perspective and incorporating relevant theories to propose blockchain solutions for CDWM and to tackle the efficiency challenges faced by the current CDWM practices. The developed blockchain-enabled CDWM framework and the detailed system architecture contribute to a deeper understanding of blockchain's role in CDW information management, thereby revealing the intricate layers and processes involved. This study thus significantly enriches the body of knowledge in CDWM from an information management perspective.

5.1.2. Practical Contributions

From a practical standpoint, the development of blockchain-based solutions for CDW information management promises enhanced traceability, transparency, and trust in CDWM processes, especially to mitigate CDW dumping and reduce carbon emission in the construction industry.

On the one hand, the blockchain-based solutions provide transparency to CDWM, thereby helping to address the principal–agent problem and enhance the data supply chain. These improvements are instrumental in fostering more collaborative approaches to CDWM and reducing CDW dumping. In CDW recycling and trading, blockchain-based solutions operate on a decentralized network, where multiple participants validate and agree on the accuracy of transactions. This practice enhances recycling and reduces CDW dumping. Blockchain-based solutions can also help certify and verify the authenticity of waste disposal records. The further use of blockchain in the industry can facilitate the implementation of incentive programs to encourage proper waste disposal practices to achieve sustainable production.

On the other hand, the use of blockchain technology in CDWM can facilitate carbon reduction and offsetting within the construction industry. Transparent records of CDW transactions and movements, maintained by a blockchain, facilitate continuous tracking of CDW and associated carbon emissions. This capability is crucial to accurately measuring and managing carbon emissions in the construction and demolition process. Furthermore, the blockchain-enabled CDWM system can incentivize sustainable practices, such as recycling or reuse, by rewarding stakeholders who contribute to a circular economy. An additional prospective application lies in carbon trading. The transparent and reliable CDW information provided by blockchain technology can facilitate the association of carbon credits with CDW, thereby potentially opening new avenues for carbon trading in the construction industry.

5.2. Potential to Improve CDWMIS with Blockchain Technology

The potential to improve the CDWMIS can be realized by improving technology management and advancing technology use.

Improving Technology Management: Through the system design and actions, it was also found that appropriate BT infrastructures, a well-developed regulatory system, governmental incentive policies, and skilled personnel, which are also confirmed by Sadeghi et al. [9] and Chauhan et al. [37], are key to improve the use of blockchain technology in the CDWMIS. These factors should be well managed when applying BT infrastructures into the CDWMIS, as technology management is a premise to effectively implement blockchain technology.

Advancing Technology Use: With the rapid development of distributed ledger technology, the most recent ledger databases such as LedgerDB and VeDB [38] can be applied into the CDWMIS. In particular, potential exists in using LedgerDB, which has a similar function to blockchain technology using distributed ledgers to provide tamper evidence and non-repudiation features but with higher performance [39]. Furthermore, the sophisticated threat model of LedgerDB can enhance the security and auditability of the CDWMIS [40].

5.3. Critical Analysis and Reflection on This Design Science Action Research

This study employed the design science method, as it focuses on the design of systems and may be in shortage with respect to empirical validation. To address such a methodological issue, this study also adopted action research to validate the design and to mitigate possible design deviation through constant interactions with the practitioners. Also, the structural design science research approach was followed as illustrated in Figure 1. Nevertheless, one important reflection from the expert panel is that the framework and system are in the experimental stage and can be better applied to practical situations with more iterations. So far, it seems this study can provide the fundamental structure for the following iterations; therefore, it can be presented as an independent design science action research study.

6. Conclusions

The construction industry, which is a significant contributor to carbon emissions, faces various information management challenges in its current practices. This study has introduced blockchain technology into CDWM to address these issues. By using a design science action research approach, it identified critical information management problems, designed a blockchain-enabled CDWM framework, and developed a system architecture for the CDWM information system. The study also clarified the impacts of the blockchain on the CDWM system and potential problems, thus demonstrating how blockchain-based solutions can enhance CDWM effectiveness, digitization, and administrative and regulatory systems. Furthermore, the integration of blockchain technology in CDWM presents unique opportunities for carbon reduction and offsetting in the construction industry.

However, this study has a few limitations. Firstly, this study focused on addressing the principal–agent issue and enhancing the data supply chain in CDWM using the blockchain. However, the systematic implementation of a blockchain-enabled system necessitates the extensive development of blockchain-based solutions, together with significant efforts and investment. For instance, introducing the blockchain into CDWM encounters organizational resistance from some actors, thereby stemming from concerns about technological risks and potential changes in interests. This is an area future research can improve. Also, as this blockchain-based CDWM solution is currently in the bidding and tendering process for a municipal-level adoption and is in an experimental stage, the further improvement of the CDWMIS remains to be clarified with the feedback of its implementation. Future research could aim to address the operational and managerial challenges, particularly in the implementation of blockchain-enabled CDWM information systems. Moreover, research can be devoted to advance blockchain use with other distributed technologies as presented in the discussion. Exploring the use of smart contracts in CDW trading and recycling also represents a promising avenue for further research, given its potential to streamline repetitive and miscellaneous procedures and its overall significance in waste management.

Author Contributions: Conceptualization, H.Y.; Methodology, X.M.; Validation, H.Y.; Formal analysis, X.M.; Investigation, H.Y.; Resources, W.D.; Writing—original draft, X.M.; Writing—review & editing, H.Y.; Visualization, W.D.; Funding acquisition, H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study is financially supported by the National Social Science Fund of China (Grant reference number: 20BGL187).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, K.; Qing, Y.; Umer, Q.; Asmi, F. How construction and demolition waste management has addressed sustainable development goals: Exploring academic and industrial trends. *J. Environ. Manag.* **2023**, *345*, 118823. [CrossRef] [PubMed]
2. Ogunmakinde, O.E.; Egbelakin, T.; Sher, W. Contributions of the circular economy to the UN sustainable development goals through sustainable construction. *Resour. Conserv. Recycl.* **2022**, *178*, 106023. [CrossRef]
3. Kanafani, K.; Magnes, J.; Lindhard, S.M.; Balouktsi, M. Carbon emissions during the building construction phase: A comprehensive case study of construction sites in Denmark. *Sustainability* **2023**, *15*, 10992. [CrossRef]
4. Ma, W.; Hao, J.L.; Zhang, C.; Di Sarno, L.; Mannis, A. Evaluating carbon emissions of China's waste management strategies for building refurbishment projects: Contributing to a circular economy. *Environ. Sci. Pollut. Res.* **2023**, *30*, 8657–8671. [CrossRef]
5. Liu, Z.; Osmani, M.; Demian, P.; Baldwin, A. A BIM-aided construction waste minimisation framework. *Autom. Constr.* **2015**, *59*, 1–23. [CrossRef]
6. Lu, W.; Webster, C.; Chen, K.; Zhang, X.; Chen, X. Computational Building Information Modelling for construction waste management: Moving from rhetoric to reality. *Renew. Sustain. Energy Rev.* **2017**, *68*, 587–595. [CrossRef]
7. Scott, D.J.; Broyd, T.; Ma, L. Exploratory literature review of blockchain in the construction industry. *Autom. Constr.* **2021**, *132*, 103914. [CrossRef]
8. Elghaish, F.; Hosseini, M.R.; Kocaturk, T.; Arashpour, M.; Ledari, M.B. Digitalised circular construction supply chain: An integrated BIM-Blockchain solution. *Autom. Constr.* **2023**, *148*, 104746. [CrossRef]

9. Sadeghi, M.; Mahmoudi, A.; Deng, X.; Luo, X. Prioritizing requirements for implementing blockchain technology in construction supply chain based on circular economy: Fuzzy Ordinal Priority Approach. *Int. J. Environ. Sci. Technol.* **2023**, *20*, 4991–5012. [CrossRef]
10. Jalaei, F.; Zoghi, M.; Khoshande, A. Life cycle environmental impact assessment to manage and optimize construction waste using Building Information Modeling (BIM). *Int. J. Constr. Manag.* **2021**, *21*, 784–801. [CrossRef]
11. Aslam, M.S.; Huang, B.; Cui, L. Review of construction and demolition waste management in China and USA. *J. Environ. Manag.* **2020**, *264*, 110445. [CrossRef] [PubMed]
12. Li, C.Z.; Zhao, Y.; Xiao, B.; Yu, B.; Tam, V.W.; Chen, Z.; Ya, Y. Research trend of the application of information technologies in construction and demolition waste management. *J. Clean. Prod.* **2020**, *263*, 121458. [CrossRef]
13. Cao, X.; Ding, Z. Management of municipal construction waste transportation by integrating ABM and GIS Model: A case study of Shenzhen. In Proceedings of the 25th International Symposium on Advancement of Construction Management and Real Estate, Wuhan, China, 28–30 November 2020; Springer: Singapore, 2021; pp. 235–253.
14. Xu, J.; Shi, Y.; Xie, Y.; Zhao, S. A BIM-Based construction and demolition waste information management system for greenhouse gas quantification and reduction. *J. Clean. Prod.* **2019**, *229*, 308–324. [CrossRef]
15. Siountri, K.; Skondras, E.; Vergados, D.D. Towards a smart museum using BIM, IoT, blockchain and advanced digital technologies. In Proceedings of the ICVISP 2019: 3rd International Conference on Vision, Image and Signal Processing, Vancouver, BC, Canada, 26–28 August 2019. [CrossRef]
16. Celik, Y.; Petri, I.; Rezgui, Y. Leveraging BIM and blockchain for digital twins. In Proceedings of the 2021 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2021, Cardiff, UK, 21–23 June 2021.
17. Berawi, M.A.; Zagloel, T.Y.; Ariq, M.N.; Sari, M. A Blockchain-based BIM model for the smart building planning process. In Proceedings of the 3rd International Scientific Conference on Innovations in Digital Economy, Saint-Petersburg, Russia, 14–15 October 2022; pp. 253–261.
18. Jiang, Y.S.; Liu, X.L.; Kang, K.; Wang, Z.C.; Zhong, R.Y.; Huang, G.Q. Blockchain-enabled cyber-physical smart modular integrated construction. *Comput. Ind.* **2021**, *133*, 103553. [CrossRef]
19. Li, X.; Lu, W.S.; Xue, F.; Wu, L.P.F.; Zhao, R.; Lou, J.F.; Xu, J.Y. Blockchain-enabled IoT-BIM platform for supply chain management in modular construction. *J. Constr. Eng. Manag.* **2022**, *148*, 0002229. [CrossRef]
20. Wu, L.; Lu, W.; Xue, F.; Li, X.; Zhao, R.; Tang, M. Linking permissioned blockchain to Internet of Things (IoT)-BIM platform for off-site production management in modular construction. *Comput. Ind.* **2022**, *135*, 103573. [CrossRef]
21. Götz, C.S.; Karlsson, P.; Yitmen, I. Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management. *Smart Sustain. Built Environ.* **2022**, *11*, 532–558. [CrossRef]
22. Figueiredo, K.; Hammad, A.W.A.; Haddad, A. Improving sustainability in the built environment through a BIM-based integration of digital twin and blockchain: An analysis of prefabricated modular construction. In *Cognitive Digital Twins for Smart Lifecycle Management of Built Environment and Infrastructure Challenges, Opportunities and Practices*; CRC Press: Boca Raton, FL, USA, 2023; pp. 101–122.
23. Shojaei, A.; Wang, J.; Fenner, A. Exploring the feasibility of blockchain technology as an infrastructure for improving built asset sustainability. *Built Environ. Proj. Asset Manag.* **2020**, *10*, 184–199. [CrossRef]
24. Perera, S.; Nanayakkara, S.; Rodrigo, M.; Senaratne, S.; Weinand, R. Blockchain technology: Is it hype or real in the construction industry? *J. Ind. Inf. Integr.* **2020**, *17*, 100125. [CrossRef]
25. França, A.; Neto, J.A.; Gonçalves, R.; Almeida, C. Proposing the use of blockchain to improve the solid waste management in small municipalities. *J. Clean. Prod.* **2020**, *244*, 118529. [CrossRef]
26. Wu, L.; Lu, W.; Peng, Z.; Webster, C. A blockchain non-fungible token-enabled 'passport' for construction waste material cross-jurisdictional trading. *Autom. Constr.* **2023**, *149*, 104783. [CrossRef]
27. Gregor, S.; Hevner, A.R. Positioning and presenting design science research for maximum impact. *MIS Q.* **2013**, *37*, 337–355. [CrossRef]
28. Hartmann, T.; Fischer, M.; Haymaker, J. Implementing information systems with project teams using ethnographic–action research. *Adv. Eng. Inform.* **2009**, *23*, 57–67. [CrossRef]
29. Peffers, K.; Tuunanen, T.; Rothenberger, M.A.; Chatterjee, S. A design science research methodology for information systems research. *J. Manag. Inf. Syst.* **2007**, *24*, 45–77. [CrossRef]
30. Spremann, P.K. Agent and principal. In *Agency Theory, Information, and Incentives*; Springer: Berlin/Heidelberg, Germany, 1987; pp. 3–37.
31. Sezer, A.A.; Bosch-Sijtsema, P. Actor-to-actor tensions influencing waste management in building refurbishment projects: A service ecosystem perspective. *Int. J. Constr. Manag.* **2022**, *22*, 1690–1699. [CrossRef]
32. Akinade, O.O.; Oyedele, L.O.; Ajayi, S.O.; Bilal, M.; Alaka, H.A.; Owolabi, H.A.; Arawomo, O.O. Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment. *J. Clean. Prod.* **2018**, *180*, 375–385. [CrossRef]
33. Wieringa, R.J. *Design Science Methodology for Information Systems and Software Engineering*; Springer: Berlin/Heidelberg, Germany, 2014.
34. Zhang, Y.; Wang, T.; Yuen, K. Construction site information decentralized management using blockchain and smart contracts. *Comput.-Aided Civ. Infrastruct. Eng.* **2022**, *37*, 1450–1467. [CrossRef]

35. Yang, Z.; Zhu, C.; Zhu, Y.; Li, X. Blockchain technology in building environmental sustainability: A systematic literature review and future perspectives. *Build. Environ.* **2023**, *245*, 110970. [CrossRef]
36. Li, J.; Kassem, M. Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. *Autom. Constr.* **2021**, *132*, 103955. [CrossRef]
37. Chauhan, C.; Parida, V.; Dhir, A. Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. *Technol. Forecast. Soc. Change* **2022**, *177*, 121508. [CrossRef]
38. Yang, X.; Zhang, R.; Yue, C.; Liu, Y.; Ooi, B.C.; Gao, Q.; Zhang, Y.; Yang, H. VeDB: A software and hardware enabled trusted relational database. *Proc. ACM Manag. Data* **2023**, *1*, 194. [CrossRef]
39. Yang, X.; Zhang, Y.; Wang, S.; Yu, B.; Li, F.; Li, Y.; Yan, W. LedgerDB: A centralized ledger database for universal audit and verification. *Proc. VLDB Endow.* **2020**, *13*, 3138–3151. [CrossRef]
40. Yang, X.; Wang, S.; Li, F.; Zhang, Y.; Yan, W.; Gai, F.; Yu, B.; Feng, L.; Gao, Q.; Li, Y. Ubiquitous verification in centralized ledger database. In Proceedings of the 2022 IEEE 38th International Conference on Data Engineering (ICDE), Kuala Lumpur, Malaysia, 9–12 May 2022; pp. 1808–1821.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.