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Blockchain Enhanced Construction Waste Information Management: A Conceptual Framework

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Abstract: Despite the large quantities of secondary materials flowing within the built environment, their actual volume and respective waste management processes are not accurately known and recorded. Consequently, various sustainability and material efficiency policies are not supported by accurate data and information-reporting associated with secondary materials' availability and sourcing. Many recent studies have shown that the integration of digital technologies such as city information management (CIM), building information modeling (BIM), and blockchain have the potential to enhance construction waste management (CWM) by classifying recycled materials and creating value from waste. However, there is insufficient guidance to address the challenges during the process of CWM. Therefore, the research reported in this paper aims to develop a blockchain-enhanced construction waste information management conceptual framework (BeCW). This paper is the first attempt to apply the strengths of integrated information-management modeling with blockchain to optimize the process of CWM, which includes a WasteChain for providing a unified and trustworthy credit system for evaluating construction-waste-recyclability to stakeholders. This is enabled through the use of blockchain and self-executing smart contracts to clarify the responsibility and ownership of the relevant stakeholders. As a result, this study provides a unified and explicit framework for referencing which quantifies the value-contribution of stakeholders to waste-recovery and the optimization of secondary construction materials for reuse and recycling. It also addresses the issue of sustainable CWM through information exchange at four levels: user, application, service, and infrastructure data levels.

Keywords: blockchain; city information management (CIM); building information modeling (BIM); construction waste management; recycling

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1. Introduction

Human activities have led to irreversible environmental damage. With a growing awareness of this damage, organizations across the world have enacted a number of environmental policies and production-emission targets. In order to meet the targets of the Paris Agreement [1], the United Nations Framework Convention on Climate Change (UNFCCC) [2] has set rigorous goals to achieve circular material flows. In addition, under the European Union Circular Economy Action Plan [3], the European Union (EU) has developed the "Roadmap to a Resource-Efficient Europe" program to enhance the use of recycled materials and the demand for secondary materials in a drive to decarbonize the environment [4]. The architectural, engineering, and construction industries oversee large amounts of materials throughout buildings and assets' lifecycle stages, including construction and demolition waste, which leads to ever-growing emissions of various pollutants and greenhouse gases [5]. A large amount of construction waste, such as engineering residue, is still generated during the construction process [6]. The disposal methods for engineering residues are mainly dumping and piling, which have caused adverse effects on the environment [7]. Therefore, the effective management of construction waste requires the adoption of sustainable and circular methods to achieve 'Sustainable Development Goals' [8]. However, coherent data and information-reporting processes associated with secondary construction materials' accessibility, availability, and sourcing have not been regulated and unified at an international scale. As such, establishing an effective and cohesive information management system has been deemed critical to improve construction waste management (CWM) and optimize the utilization of associated secondary materials.

Applications of digital technologies were deemed as means to potentially overcome material efficiency challenges with the advent of the industrial digitization era [9]. It has been argued that building information modeling (BIM) promotes sustainable waste management by optimizing the entire process of construction projects [10]. As a platform for the analysis and planning of sustainable urban development, city information management (CIM) applies the principles of BIM to the urban level and improves public services [11]. In addition, blockchain technology acts as a digital recording tool that allows multiple parties to address complex problems in the value chain [12,13]. More broadly, digital technologies have led to a more efficient way of working, which uses an integration of computer technology and information technology to build a decision support system, enhancing sustainable construction management [14]. Previous research reported that the application of digital technology in the field of sustainable CWM has the following benefits [15]: predicting the environmental impact of construction projects using simulation technology, measuring the impact of construction in real time, and supporting the adoption of measures to mitigate the adverse impacts on the environment.

At present, the application of full digitalization in CWM is still at an early nascent stage. However, with the gradual maturity of digital technologies, all stakeholders involved in design, construction, and waste disposal can jointly manage the project via a CIM platform, in which project data and material information can be interconnected. Current studies on blockchain are mainly concentrated on analyzing the mechanisms of cryptocurrencies and computer network security [16,17]. On the contrary, there are few concerns about the impact brought by the application of blockchain [18,19]. Additionally, there are several blockchain standards that have been introduced to regulate the business collaboration platform for engineering projects, including ITU-T blockchain standard, ISO/TR23244 [20], IEEE blockchain standard [21], JR/T 0184-2020 [22], JR/T 0193-2020 [23], and ISO/AWI TS 23635 [24]. However, a comprehensive methodology that applies blockchain to CWM for technical developers is currently missing [25]. Secure, tamper-proof lifecycle information and comprehensive guidelines are necessary to make sure that the recycling responsibility will be supported by policies and incentives. Therefore, the purpose of this paper is to propose a blockchain-enhanced construction waste information management conceptual framework (BeCW) towards sustainable urban development. This framework includes a WasteChain for providing a unified and trustworthy credit system for evaluating construction waste recyclability to stakeholders.

The paper is organized as follow. In Section 2, the methodology of this research is described. Section 3 presents the result of the literature review. Thereafter, the system model and the preliminary framework for the blockchain-enhanced construction waste management framework is presented in Section 4. The framework evaluation is presented in Section 5, and discussions and conclusions round out the paper in Sections 6 and 7.

2. Methodology

A mixed research method was adopted for this study to establish a conceptual BeCW framework. A literature review was conducted to set the scope for the research and map out the landscape of the various topics related to construction waste and information management. This is discussed in Section 3 below, which has the information on the structural elements of the BeCW conceptual framework. CIM has been deemed as a potential enabler to digitize construction components that can be linked with other technologies. Information across a building lifecycle is updated and stored in an asset database of construction waste, which is then linked to the WasteChain. The proposed BeCW framework includes a WasteChain with two sub-chains for achieving the functionality, known as Waste-Creditchain and Waste-Infochain, which provides a possible explanation of how CIM fits in this conceptual BeCW framework and how it connects different stakeholders.

As shown in Figure 1, the proposed BeCW conceptual framework has two levels: (1) the high-level framework concentrates on the strategy of CWM, (2) the low-level framework sets out detailed processes of CWM.

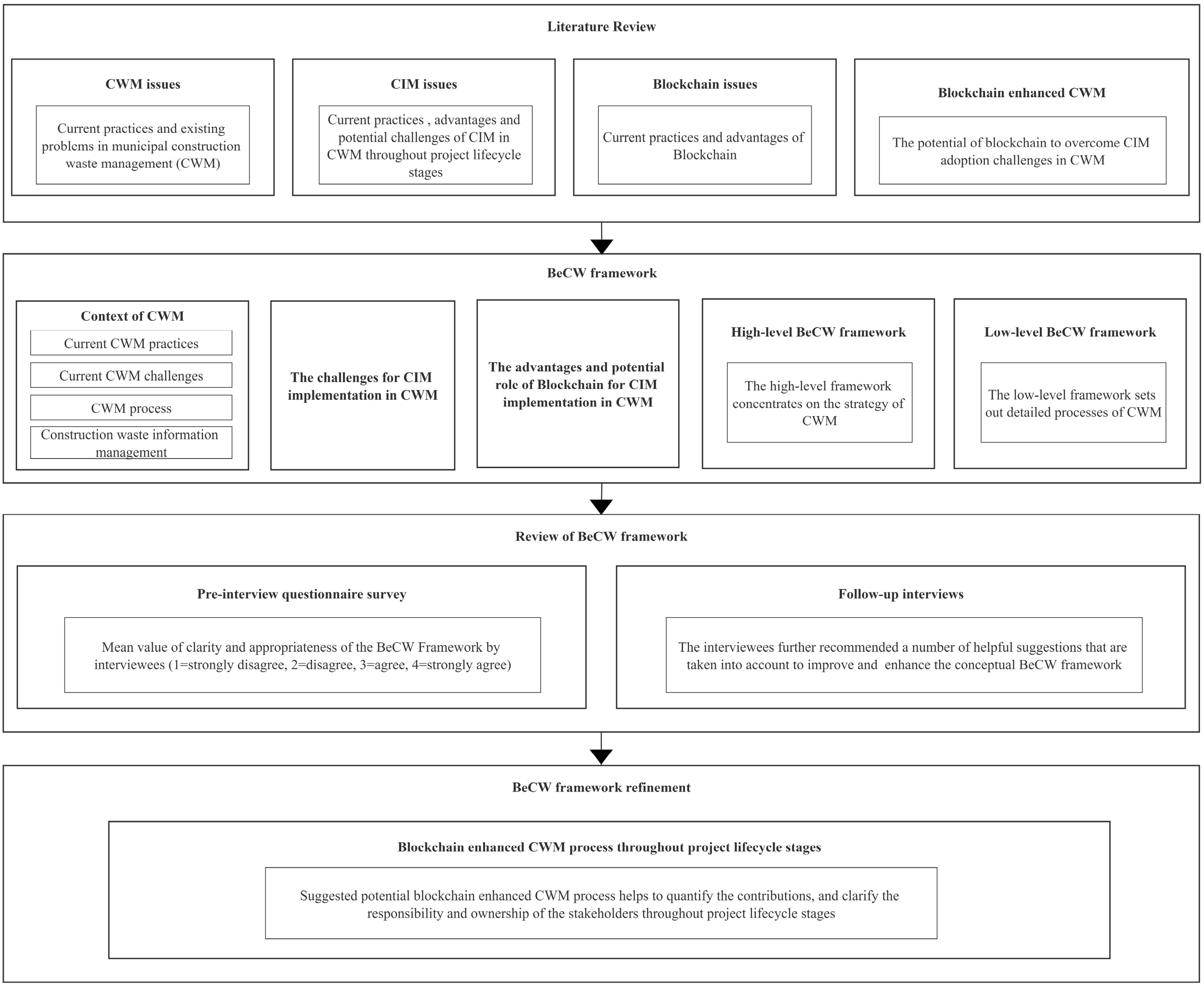

Figure 1. The blockchain-enhanced construction waste information management conceptual framework (BeCW) development and review flow chart (generated by the authors).

The BeCW framework was presented and evaluated at the "2021 China Society of Industrial and Applied Mathematics Blockchain Technology and Application Summit Forum" (CSIAM-BTAF 2021) [26]. The BeCW framework was academic- and industry-reviewed via a pre-interview questionnaire and follow-up semi-structured interviews, involving six blockchain industry experts and academics who voluntarily participated in the framework review process. This helped to further refine the BeCW framework. The aim of the pre-interview questionnaire was to evaluate the BeCW framework in terms of clarity of structure, comprehensibility of content, and clarity of processes, while the objective of the follow-up semi-structured interviews was to gauge recommendations on the improvement of the framework.

Subsequently, means comparison analysis was adopted for the quantitative questionnaire data; and content analysis using NVivo software was conducted for the qualitative interview data. In this study, Nvivo11 software was used as an auxiliary analysis tool to collect, analyze, and code the interview data and construct the model step-by-step according to the method of rooting theory. Lincoln and Guba (2012) [27–29] had developed a criteria in qualitative research to establish trustworthiness in the previous study, which is known as credibility, dependability, confirmability, and transferability. In order to adapt the criteria, this study selects those strategies that applied to the study systematically. Table 1 illustrates which strategies were adopted in this study.

Table 1. Key data analysis trustworthiness strategies adopted for this study.

Criteria	Purpose	Strategies Applied in This Study
Credibility	To guarantee the results (from the perspective of the participants) are true, credible, and believable	Ensuring the investigators had the required knowledge and research skills to perform their roles Asking interviewers to send all the notes to the researcher for analysis and storage, and ensuring that the entire interview process is recorded Prolonging and varied engagement with each setting
Dependability	To ensure the findings of this qualitative inquiry is repeatable	Preparing detailed drafts of the study protocol throughout this study Developing a detailed track record of the data collection process Measuring coding accuracy and reliability of the research team
Confirmability	To extend the trustworthiness that the results would be confirmed or corroborated by other researchers	Applying several techniques (methodological, data source, investigators and theoretical)
Transferability	To extend the degree to which the results can be transferred to other contexts or settings	Purposeful sampling to form a nominated sample Quantifying the interview text

The development and review process of the BeCW framework is reported in Sections 4 and 5 below.

3. Results

3.1. Construction Waste Management (CWM)

3.1.1. Current CWM Practice

A circular economy aims to circulate products and materials at their highest values. This achieved through sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as possible. The circular economy is proposed to maintain the maximum utility of resources and materials in the closed-loop of the product's lifecycle and to minimize the consumption of resources [30], in which waste is considered as a renewable resource [31]. The introduction of the circular economy concept has a positive impact on the economy, society, and the environment [32].

CWM is undergoing a shift from simple material collection and sorting to sustainable recycling systems. The closed-loop management of construction materials can be achieved through waste reduction, recycling, and reuse when construction materials reach their end-of-lifecycle [33]. In 2015, the European Union adopted a series of guidelines for recycling construction waste to reduce the landfills disposal [31]. However, the recycling and reuse of construction waste is limited to the efforts of individual organizations [34].

The 3R (reduce, reuse, recycle) waste management principle is a management model for waste treatment under the concept of a circular economy [35]. In line with the 3R principle, a hierarchical model has been developed for construction and demolition waste disposals by evaluating the environmental impacts of various construction waste disposal modes [36]. In construction projects, different geological conditions, construction techniques, and construction processes lead to variability in the quality of engineering residues [37]. Therefore, aligning the hierarchical model of construction and demolition waste, the disposal methods of construction waste can be divided into five levels: reduction, reuse, recycling, incineration, and landfill. Reduction requires the use of fewer raw materials and energy inputs in construction [38]. Reuse involves applying the material multiple times for the same purpose or for other uses [39]. Recycling refers to the return of construction waste to the supply chain by changing its original form [38]. The process of incineration extracts energy from municipal construction waste, but the toxic gases produced during the incineration pose a threat to both human health and the environment [36]. Landfilling is only considered when other options are unavailable for the disposal of municipal construction waste, which is not only taking up large amounts of land resources, but also seriously contaminates soil and groundwater [40].

In order to promote waste management in the construction industry, government and authorities have also proposed some instruments and measures, including deposit-refund systems (DRS), subsidies, a tradable permit system, etc [41]. These practices use different models and methods to stimulate waste efficiency. Furthermore, the case in the UK of the recovery N = note system (RNs) provides flexibility to various stakeholders to participate in the waste management process [41]. However, there are limitations for these systems and methods. For example, stakeholders cannot verify if a material is recyclable. There is mistrust between project actors, namely contractors and clients, on the type and recyclability of waste materials.

3.1.2. Current CWM Challenges

Currently, the increasing demand for infrastructures and transportation due to the acceleration of urbanization process has led to the expansion of underground structures and assets, namely tunnels construction [7]. Underground construction generates significant amounts of engineering residues, including engineering dregs and slurry, accounting for 15 to 20% of the total construction waste generation [6,7], which has been treated as dumping and piling as the main disposal methods [42].

A number of developed countries have made noticeable CWM best practice. The United States has developed as LEED (leadership in energy and environmental design), which is the most widely used green building rating system in the world, recognizing buildings that adopt a whole-systems approach aimed at changing how materials flow through society, resulting 'zero waste' [43]. The UK Green Construction Board has recently published 'The Routemap for Zero Avoidable Waste in Construction' (UKGC, 2022) [44] to attain the government's resources and waste strategy (2018) ambition to "eliminate avoidable waste of all kinds by 2050′ in England". This includes waste from all sectors of society, including the construction sector (both buildings and infrastructure). In contrast, the CWM performance in many developing countries is still inappropriate [45]. There is a common agreement in in the literature that construction waste should be considered as a valuable resource. Indeed, treated engineering residues can be used as aggregates, as well as secondary raw materials for industrial production, road construction, and railway embankments [7,42]. A closed-loop construction and recycling demolition management for mixed recycled aggregates (MRA) can lead to a greener environment [46]. However, many governments have not established guiding standards and specifications for construction waste recycling and treatment. In addition, due to the fragmentation of construction projects at various stages, it is difficult to track information about on-site waste generation, resulting in a lack of transparent, credible, traceable information throughout the project lifecycle [47]. Therefore, stakeholders are faced with difficulties to verify the authenticity of the information during construction in which improper waste disposal is hard to avoid [48]. CWM spans the entire lifecycle process of construction projects and is required to be considered during the design stage [10]. As such, planning and scheduling for reuse and recycling in advance are required for construction waste that cannot be avoided.

3.1.3. Current CWM Process

The goals of sustainable construction include the recycling and conversion of waste into usable resources and the reduction of the requirement for raw materials. Construction waste recycling processes require consideration of the construction scheme, waste generation estimation, chemical and environmental analysis, waste quality assessment, experimental treatment, and experimental testing to achieve cost effectiveness and material efficiency. The introduction of CIM in the process of CWM assists in the management of the waste recycling process. Project stakeholders including architects, structural designers, municipal engineers, materials engineers, contractors, clients, and government officers can query and manipulate the entire project process via CIM [49]. The entire CWM process is illustrated in Figure 2, in which the main process of construction waste recycling has the following steps:

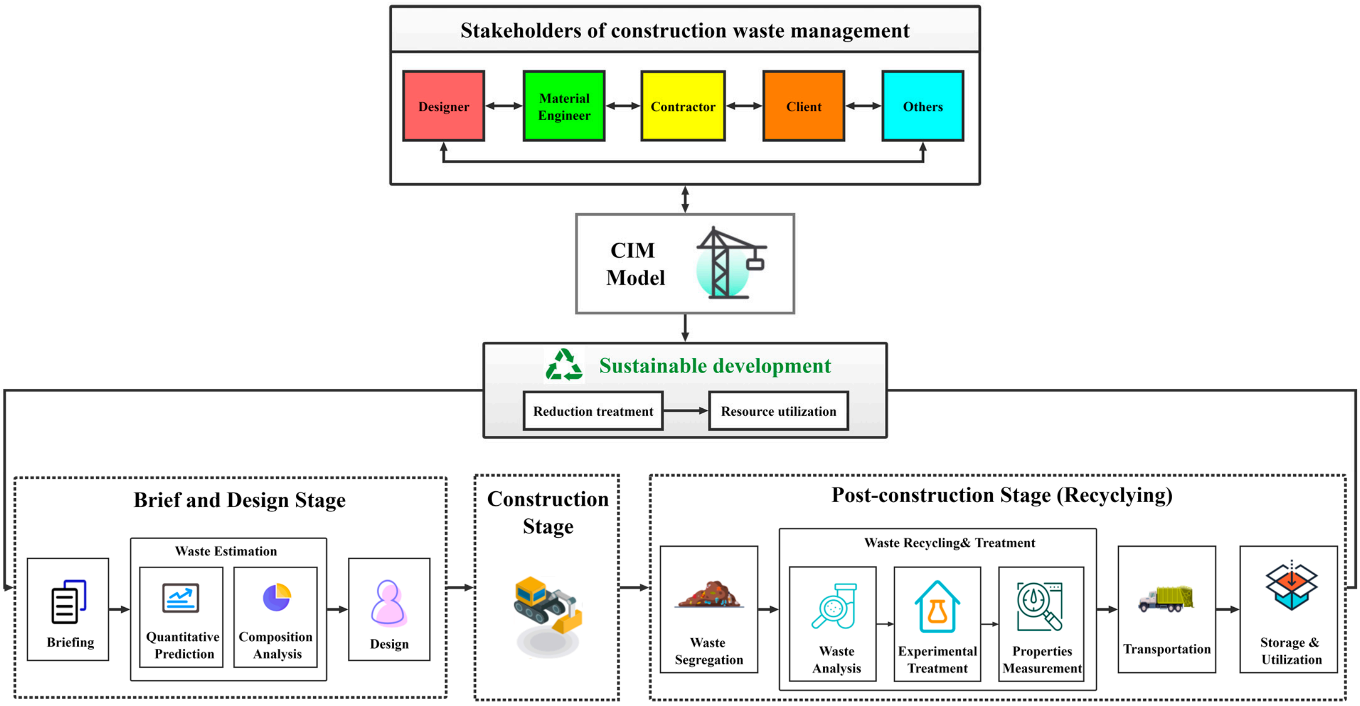

Figure 2. Construction waste management (CWM) process (devised by the authors based on the literature).

1. Selecting the optimal construction scheme. The 3D model allows for the simulation of the shield excavation scheme [50];
2. An evaluation on waste generation based on the optimal construction scheme. CIM facilitates the estimation of waste generation based on the previous project records and ground data [51], which helps in reducing waste generation;
3. The assessment of construction waste quality. The chemical and environmental analysis of construction waste and the surrounding environment of the construction site is required to assess the waste quality and determine the waste composition, in which different construction techniques and geological factors affect the quality of the engineering residue [37];
4. Waste recycling treatment. The process entails removing impurities from the waste that affect subsequent reuse. For example, tunnel mucks usually have a high iron con-

tent and a high solubility, which could be diminished by acid treatment and reduction roasting treatment so that it can be reused in construction, sanitary construction, and other industries;
5. Physical–mechanical parameters and quality assessment. The treated material needs to undergo tests such as deformation modulus, mechanical resistance, strain and compressive strength, bulk density, water absorption, and whiteness. These test results must meet the requirements specified by national and international standards;
6. Management of experimental data and material information, and;
7. Selecting material transportation and storage plans.

3.1.4. Construction Waste Information Management

CIM serves as an integrated platform with the advantages of data sharing and entire lifecycle management [52]. It is an interoperable urban modeling and prediction platform composed of the BIM, geodatabase, geographic information system (GIS), CAD software, and visual programming (VPI) [53]. The existing representative CIM model divides the city system into several sub-modules, including the building, road, pile foundation, and drainage modules [49]. The function of CIM in construction management is similar to that of BIM, which can integrate data models into a unified platform and build an integrated database. This would enable stakeholders involved in the construction process to access information and jointly participate in the decision-making process [54].

The ultimate goal of CWM is to close the loop of material use and to reduce unnecessary waste [30,48]. Recently, an increasing number of studies on CIM have focussed on the application of CIM to the field of construction management. Yosino et al. [55] have proposed to reduce the generation of unnecessary municipal solid waste by integrating BIM and GIS into CIM, in which a CIM simulation was used to predict the amount of waste generation and analyze the waste collection routes. Guerra et al. [39] implemented an integrated 4D-BIM with temporal-based algorithms to estimate the amount of waste generation and to arrange the reuse and recycling processes of waste in advance to minimize waste disposal in landfills. In the case of municipal sewage and sludge system management, Melo et al. [56] applied CIM to provide accurate information during the project design phase for decision-making by stakeholders. Scenario simulation and data analysis can be performed by integrating information from all aspects of a project in CIM, which assists stakeholders in decision-making and whole lifecycle control over the course of the CWM process. The advantages of CIM in CWM have been widely studied, and they include:

- Three-dimensional visualization. CIM intuitively and efficiently conveys information to users (stakeholders) by transforming information and data into three-dimensional image means to demonstrate the structure of the construction project [57];
- Model integration and collaboration. BIM integrates information from various sources so that all information can be transmitted directly and used collaboratively on the same platform [10,58];
- Simulation and data analysis. The CIM platform can be applied for construction schedule simulation, site analysis, and clash detection during CWM [10];
- Quantity calculation and waste estimation. Construction waste generation can be estimated in advance based on the information collected by the BIM-assisted platform, where the generated results provide guidance for the subsequent project construction [51];
- Information management. CIM integrates information into a unified platform for information management [59];
- Spatial query and analysis capabilities of GIS. CIM integrates the indoor and outdoor information of the city, including space, latitude, and longitude; as such, stakeholders can access and manage the spatial information of the city in the CIM platform [56]. Furthermore, CIM assists construction projects with waste quality assessments, in which the proportion and quality of the engineering residues produced during construction depend on the excavation techniques and the geological factors of the construction

location [37]. Hence, construction techniques and geological conditions should be considered when recycling construction waste.

- Whole lifecycle control in construction projects. The integration of BIM and GIS achieves a digital representation of all aspects of the city to form a visible, operational, controllable, and predictable digital twin city [60]. Thus, the project planning and management process will leave traces on the CIM system that assists the visual control of the entire lifecycle in CWM.

3.2. The Challenges for City Information Management (CIM) Implementation in CWM

Although the implementation of BIM and GIS in construction projects has gradually matured, the CIM implementation that integrates BIM and GIS in construction projects faces a number of practical challenges, which include:

1. Technical challenges of CIM implementation:

- Lack of a framework and strategy for implementation. Currently, the application of CIM in CWM is still in its infancy, and as such it lacks a comprehensive and strategic framework for theoretical guidance [61];
- Interoperability of CIM. CIM is impeded by fragmented collaboration, which leads to incoherent and disjointed information due to the complexity of the data exchange between the information modeling software and projects [62]. In addition, tasks with different priorities bring difficulties in team communication and collaboration [63]. Therefore, the data need to be kept unaltered during the transmission process to create a CIM environment that facilitates business collaboration;
- Poor model quality and information asymmetry. There is an information gap in CWM, and the exchange of information between stakeholders is hindered, which has led to the predominance of waste disposal in landfills [63];
- Data availability, accuracy, and manageability [61]. The accuracy and manageability of construction data is a significant challenge [64]. The price and use of construction waste can be influenced by the type and quantity of the original material;
- Cyber security. Due to the rise of the sharing economy, CIM databases are threatened by theft and tampering [65].

2. Practical challenges faced by stakeholders:

- Extended responsibility and CIM contracts. Stakeholders such as clients, contractors, suppliers, and designers have the responsibility to reduce the generation of construction waste [66]. The unclear allocation of responsibilities between stakeholders is a key barrier in current CWM practice [67], in which the premise of waste recycling is to ensure that liability can be defined by contract;
- Intellectual property and value distribution. Value embodiment motivates stakeholders to participate in the recycling process of construction waste. Intellectual property is a prerequisite for the distribution of value, which not only increases the intrinsic motivation of designers, but also increases the motivation of related project stakeholders [68];
- Information model ownership management. Legal uncertainty is a major obstacle to BIM implementation. The implementation of CIM requires building trust between various stakeholders [69].

3.3. The Advantages and Potential Role of Blockchain for CIM Implementation in CWM

3.3.1. Blockchain Technology and Smart Contracts

Blockchain is a distributed ledger technology that allows data to be exchanged through multiple nodes [70]. Research has been conducted in the fields of cryptography, mathematics, and algorithmic modeling to explore the applications of blockchain technology in different economic sectors, including construction [71]. Smart contract protocols and peer-to-peer networks in blockchain technology work together to enhance the security of transactions [70]. In addition to the guarantee of transaction security, blockchain helps to quantify the value contribution of users, and greatly enhances the innovation potential of enterprises. Additionally, blockchain technology tracks the entire value chain, which allows for inventions that cannot be patented to still be protected by the network [72]. In general, blockchain technology has the following strengths [73]: decentralization, transparency, autonomy, immutability, and anonymity. Nowadays, blockchain is constantly being employed in various fields, such as energy, supply chain, healthcare, and the construction industry [70].

The concept of smart contracts replaces third-party intermediaries as a set of coded protocols, where users specify rules for managing transactions and automatically execute contract commands through the computer [74]. When executing transactions, a smart contract helps to reduce the cost of fulfilling the constraints set by specific policies and rules [75]. In addition, since smart contracts can automatically execute contract commands, they reduce the problem of extortion faced in trading [74]. The advent of smart contracts has greatly eliminated errors in transactions and enhanced trust and fairness among stakeholders.

3.3.2. Blockchain Networks

Blockchain networks can be classified into three types based on node access rights and transaction rights, which are public, private, and consortium blockchains [76], as shown in Table 2.

Table 2. Three types of blockchain network (devised by the authors based on the literature).

Blockchain	Read & Write Access	Consensus Process	Strengths	Limitations
Public blockchain	Open to all members of the network, without the need for permission from any institution	Everyone can join the consensus process	Transparency, openness, effective accountability, multi nodes	Limited transaction processing speed, high processor requirements, limited scalability
Private blockchain	Access within the organizer is private, only authorized users can access and read information	Nodes within a pre-selected organization	Privacy, security, high performance and efficiency	Deviation from the concept of decentralization, fewer nodes, expensive operating costs
Consortium blockchain	Users can only participate in transactions with the permission of the system	Pre-selected nodes in the consortium organization	High scalability, short transaction latency, efficient consistency management, moderate operating costs, privacy	Not completely decentralized

1. Public blockchain

Users of the network in a public blockchain are allowed to access the information on the blockchain without permission or authentication [76]. Nowadays, the public blockchain is frequently applied in the construction industry for government procurement due to its high transparency and effective accountability [77]. However, the current public blockchain still has problems in terms of high processor requirements, limited transaction processing speed, and scalability [78].

2. Private blockchain

In a private blockchain, the access level and other permissions of users have been predetermined and authorized [79]. Transactions in a private blockchain have the advantages of high privacy, security, and efficient consensus mechanisms [80]. Thus, the private blockchain guarantees the confidentiality and integrity of sensitive information, such as financial data and legal contracts, in the construction industry. However, the private blockchain has fewer nodes and requires huge operating costs compared with the public blockchain [81].

3. Consortium blockchain

The network characteristics of the consortium blockchain are similar to those of the private blockchain, where users in the network have different levels of access to information [76]. A portion of users are allowed to view all transaction information, while another portion of users can only view partial transaction information or individual nodes [78]. The consortium blockchain has the advantages of good scalability, short transaction latency, and efficient consistency management [82]. In the construction industry, the consortium blockchain increases transparency and collaboration among stakeholders.

3.3.3. Implementation Conditions of Blockchain Technology

Blockchain is not the only solution to the problems that arise from data management and transactions in CWM. A project can be considered to require blockchain technology only if the project situation meets three or more of the following criteria [83]:

- Multi-party data storage and update requirement. The transactions and operations performed by multiple stakeholders need to be recorded and stored.
- Consensus and validation requirement. When it is necessary to broadcast the affairs of stakeholders and to build trust between different parties, the actions and information of stakeholders need to go through a validation process and be documented.
- Time-limitations of transactions. The time delay of transactions will affect the project.
- Collaboration requirement. Transactions in projects are created by the interaction of multiple stakeholders and depend on their interactions.

If the CWM and construction project involves a number of stakeholders, transaction time and cost, and massive amount of information, the blockchain technology can be introduced and implemented for the project.

3.3.4. The Potential of Blockchain to Overcome CIM Adoption Challenges in CWM

The construction industry still lags behind other industries in adopting blockchain technology [84]. Most of the current research on blockchain applications in construction management has focused on construction material distribution and construction management [85], in which integrating a construction platform with blockchain technology can improve project traceability [86]. As such, blockchain technology has the following advantages:

1. Blockchain technology provides complete shared data to the users, and the information in the network is transparent to all users [87].
2. Data in the blockchain network are encrypted and stored permanently, which greatly reduces the cost of information verification and improves network security. In the material supply chain, information such as material information usually requires the intervention of a trusted third-party intermediary to confirm whether the information is true. Therefore, users can query past information and verify the authenticity of the information without relying on a third party. This avoids the problem of high fees due to third-party information monitoring [88].
3. Blockchain technology lessens the degree of information asymmetry. The authenticity of information verified by multiple parties is improved because of the large number of members on the blockchain [19]. This facilitates mutual supervision among multiple stakeholders.
4. Blockchain technology addresses the ethical problems between enterprises, governments, and clients [89]. After the material information is uploaded on the blockchain, it is clear whether the enterprise has adopted green production technology.

Hence, blockchain technology has the potential to enhance CIM adoption for CWM. The potential of implementing blockchain to overcome the challenges of CIM adoption in CWM is summarized in Table 3.

Table 3. The potential of implementing blockchain to overcome the challenges of city information management (CIM) adoption in CWM (devised by the authors based on the literature).

Advantages of Blockchain	Functions	Challenges of City Information Management (CIM) Adoption in CWM
Encryption of transactions and data	Data in the network are encrypted with a hash function and stored permanently	Cyber security
Multiple information nodes	Decentralized information is stored on different nodes, providing a basis for members in the network to share data	Data availability, accuracy, and manageability, interoperability of CIM
Information is transparent to all members	All users or permissioned users in the network can access the information stored in the ledger	Information asymmetry, data availability, accuracy, and manageability
Prevention of violations	Any violations or discrepancies will be immediately posted to the network participants	Model ownership management
Low risk of failure	Data information is transparent, controllable, and tamper-proof, and the value contribution of participants is attributed to the entity	Intellectual property and value distribution, model ownership management
Reduce human error	Any changes are reviewed by all users of the system, and algorithms in the network can identify outliers	None
Smart contracts	Terms and orders (e.g., tariffs, trade policies, compliance agreements) are written by coded protocols, users specify the rules of the transaction, and the computer automatically executes the contract orders	Extended responsibility and CIM Contracts
Synchronize transaction information	The blockchain provides a public ledger that is synchronized and updated for all users, allowing them to check past transactions at any time without relying on third parties.	Information asymmetry

4. The Conceptual Blockchain-Enhanced Construction Waste Management (BeCW) Framework

4.1. System Model

In traditional construction projects, there are few continuous flows of data in the project database because stakeholders manage the relevant data individually [48]. In addition, the information in the project database is susceptible to arbitrary tampering [85]. However, the adoption of blockchain technology provides a ledger shared by all network members. Hence, WasteChain, a model of a CWM system, has been developed based on blockchain networks, as shown in Figure 3, which consists of a public blockchain and a consortium blockchain. This system model ensures the complete storage of relevant data at each stage of construction projects and guarantees the transparency and traceability of material information. WasteChain is a blockchain for contractors, designers, engineers, and manufacturers to publish their means of materials, and for stakeholders to check the credit of recycled material or company. Waste-infochain is a consortium blockchain for recording project design documents, construction scheme documents, project contracts, waste disposal information, and material information. The members in the consortium blockchain, including contractors, designers, engineers, and manufacturers, are required to upload and publish their waste disposal information into Waste-infochain. Changes in design schemes and material handling can be viewed on the chain. In addition, Waste-Creditchain is a public blockchain for storing waste information and waste disposal information, which allows all members to access information and data on the chain to check waste disposal information and manufacturer credit. As such, blockchain ensures that the information on the WasteChain is true and accurate.

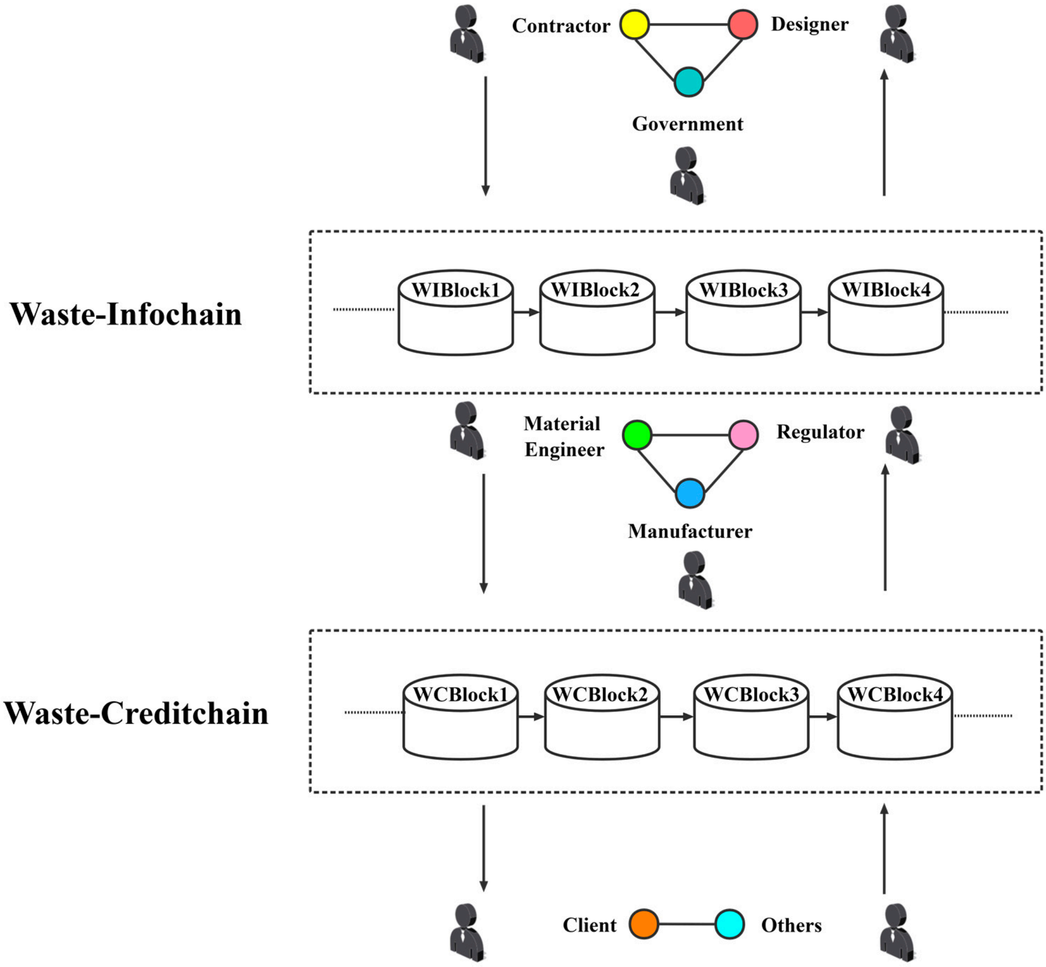

Figure 3. A CWM system model based on blockchain networks (WasteChain) (generated by the authors).

Further, project stakeholders form the WasteChain, such as designers, material engineers, contractors, and manufacturers, and are required to continuously provide information on waste processing, which is verified by all the consortium members. Clients are able to obtain product data to comprehend the process of waste treatment, but cannot publish or verify information on the nodes. In addition, government officers and regulators in the blockchain network can act as regulators to verify the authenticity and validity of information such as project contracts and waste disposal.

The information is stored in a Merkle tree, which contains the prehash, hash, last hash, timestamp, etc. The smart contract on Waste-Infochain forces the stakeholders to update and send information to Waste-Creditchain. Furthermore, users on Waste-Creditchain update the credit information by broadcasting it to the P2P network. Transactions are then encapsulated and written on blockchains, where the consensus process will check and verify to produce a new block. The WasteChain workflow is depicted in Figure 4. An example of blockchain-stored information between stakeholders is shown in Figure 5.

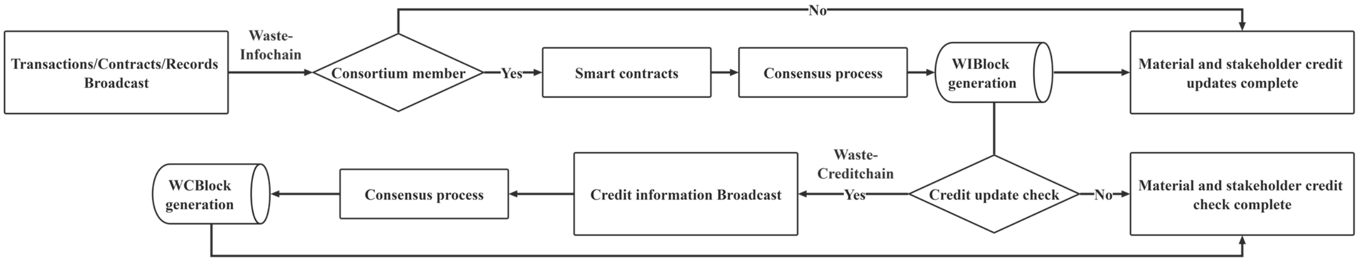

Figure 4. The workflow of WasteChain (generated by the authors).

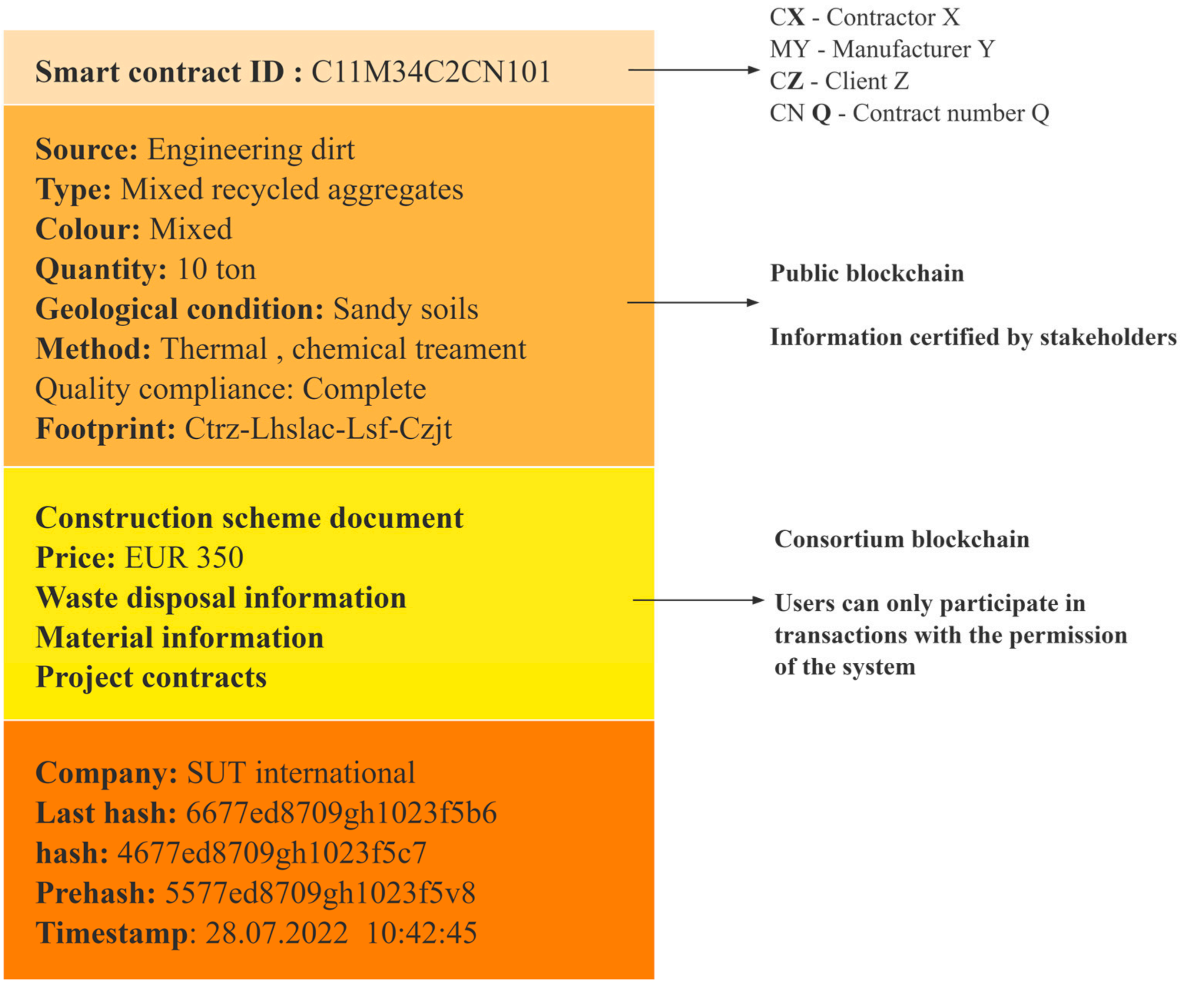

Figure 5. Example of blockchain stored information (generated by the authors).

WasteChain was proposed to improve project traceability, and clarifies the responsibility and ownership of stakeholders for addressing construction waste causes as listed in Table 4 throughout project lifecycle stages, i.e., brief and design stage, construction stage, and post-construction stage.

Table 4. Coded construction waste causes throughout construction lifecycle stages in the blockchain-enhanced CIM for the CWM (BeCW) framework (generated by the authors).

Project Lifecycle Stages	Construction Waste Causes	Code
Brief and design stage	Lack of clear objectives for MCWM [10,90]	A2
	Design problems due to communication and collaboration difficulties between different stakeholders (e.g., architects, material engineers, and contractors) [90,91]	A3
	Various interventions make design and project data exchange difficult [92]	A4
	Unclear responsibility of waste [93]	A5
	Lack of feasibility study for CIM application in MCWM [50]	A6
	Failure to clarify project requirements [94]	A7
	Lack of advanced material cost-benefit analysis based on site analysis and past data [95]	A8
	Design complexity due to the difficulties of coordination and communication [96]	A9
	Unpredictable virtual waste generation due to design changes, lack of space concept, and unclear material usage [97]	A10
	Detect collision issues early in the design process to reduce design changes and rework in construction [50]	A11
Construction stage	Determining the best construction plan has become the most important strategic issue in MCWM [50]	B1
	Multiple construction requirements increase the difficulty of construction [50]	B2
	Some duplicated and unnecessary construction procedures lead to a waste of resources and increased costs [98]	B3
	Data loss may occur during construction data exchange [48]	B4, B5
	Lack of on-site inspections and design changes leads to unnecessary procedures [99]	B6, B7
Post-construction stage	Lack of coordination and communication [90]	C1
	Lack of advanced predictions of hazard occurrence [50]	C2
	Construction equipment and hazardous areas are difficult to search [50]	C3
	Lack of a shared database, and the information is vulnerable to tampering [87,88]	C4, C5, C6, C7

4.2. The BeCW Framework

The conceptual BeCW framework has two levels: a strategic high-level framework and a detailed low-level framework, which includes various processes and coding systems across the lifecycle stages.

4.2.1. High-Level Blockchain-Enhanced CIM for CWM (BeCW) Framework

The high-level BeCW framework, as shown in Figure 6, proposes a strategic guidance for CWM and assists in the decision-making process of CWM across project lifecycle stages: brief and design stage, construction stage, and post-construction stage.

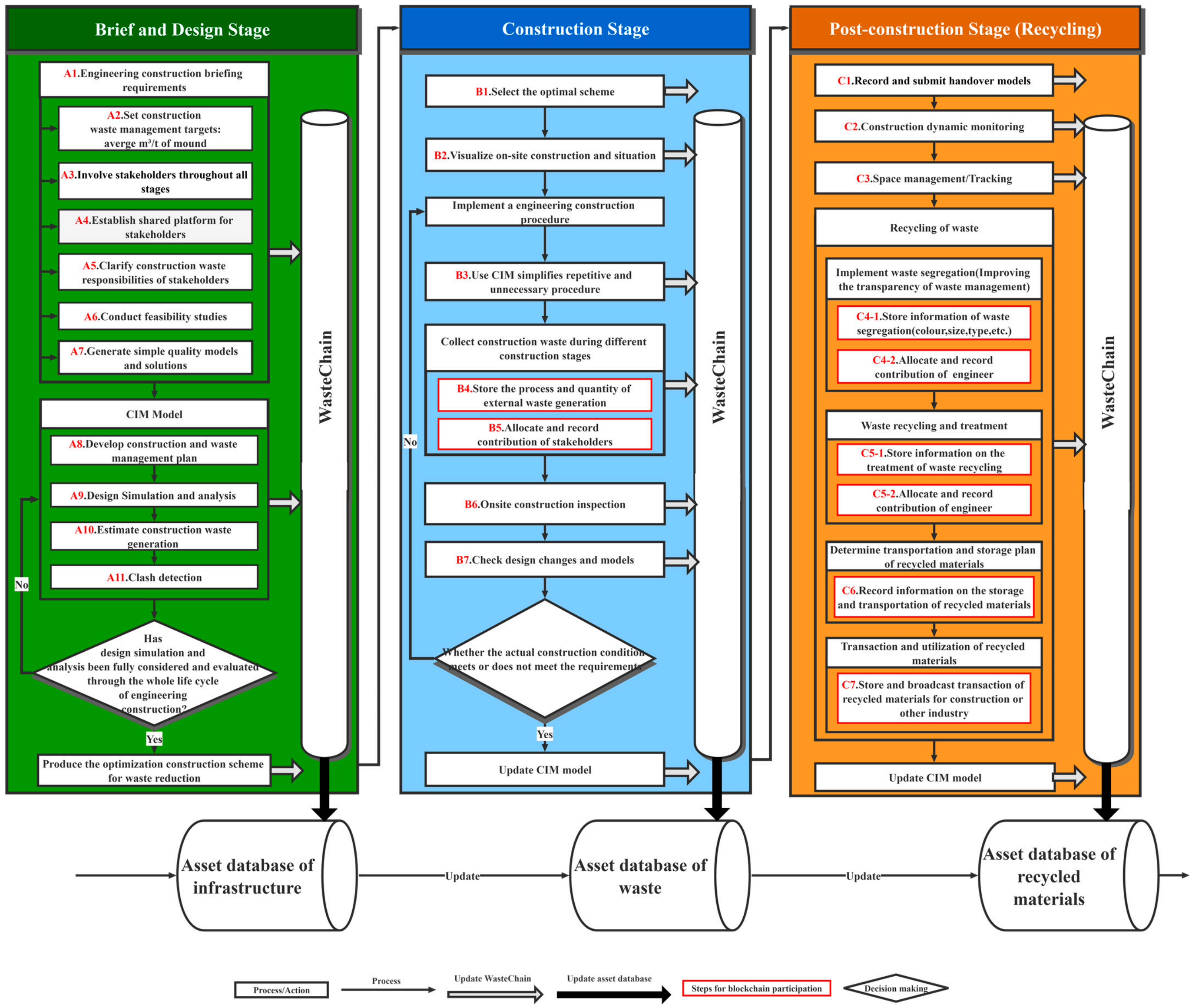

Figure 6. High-level BeCW framework.

- Brief and Design stage

As shown in Figure 6, the brief and design stage in the high-level BeCW framework is divided into two parts: specifying engineering construction briefing requirement; and the CIM model. The project briefing requirements for improving CWM encompass six specific improvement measures: setting construction waste management targets; involving all stakeholders throughout all stages; establishing a shared platform for all stakeholders; clarifying the construction waste responsibilities of stakeholders; conducting feasibility studies; and generating simple quality models and solutions, which are coded in Table 3. Details of these improvement measures are presented in the low-level BeCW framework brief and design stage.

- Construction stage

The seven measures to improve CWM, which are shown in Figure 6, comprise: selecting the optimal scheme; visualizing on-site construction and situation, using CIM to diminish repetitive and unnecessary procedures; storing the process and quantity of external waste generation; allocating and recording the contributions of stakeholders; on-site construction inspection; and checking design changes and models. Details of these improvement measures are presented in the low-level BeCW framework construction stage.

- Post-construction stage

At the post-construction stage, seven specific CWM improvements are shown in Figure 6. These improvements are designated to address the identified construction waste causes, as listed in Table 3, and include: recording and submitting handover models; construction dynamic monitoring; space management; storing information of waste segregation and allocating the contributions of engineers; storing information on the treatment of waste recycling and allocating contribution; recording information on the storage and transportation of recycled materials; and storing and broadcasting the transaction of recycled materials for construction or other industries. Details of these improvement measures are presented in the low-level BeCW framework post-construction stage.

4.2.2. Low-Level Blockchain-Enhanced CIM for CWM (BeCW) Framework

As shown in Figures 7–9, the low-level BeCW framework contains the detailed CWM process that is facilitated by blockchain-enhanced CIM operations in three stages: the brief and design stage, construction stage, and post-construction stage.

- Brief and Design stage

As shown in Figure 7, the associated improvement measures are proposed for the problems that designers, engineers, and contractors may encounter in the brief and design stage. The first step is to clarify the construction briefing requirements and set construction waste targets based on the requirements of the clients. Ineffective communication causes failure to identify the requirements of clients, which ultimately leads to design changes during the construction stage. CIM provides a shared platform for designers, contractors, and other stakeholders, and clarifies the construction waste responsibilities of stakeholders to address these problems. This is followed by feasibility studies that are required to be conducted before the technical design, generating simple quality models for the construction solution. In the CIM model, a 3D visualization model is created via databases and software, such as BIM and GIS. Material cost-effective analysis is performed in advance based on on-site analysis and data collected from sensors to address a variety of complex design issues that may be encountered based on 3D parametric modeling. Subsequently, design simulation and analysis will be conducted in the CIM platform, which will produce a virtual waste evaluation report to provide a basis for subsequent excavation scheme and MCWM strategies. The steps for estimating the total amount of waste generation, such as engineering residues including engineering dregs and slurry from the construction, are as follows:

a. Occurrence predictive model for the infrastructure such as construction sidewalks or heavy-duty sidewalks to be paved

- n: The number of construction areas;
- j: A construction area;
- S_{1j}: The jth construction area (m^2);
- S_{2j}: The jth heavy-duty construction area (m^2);
- h_{ij}: The average elevation of the jth construction area (m);
- h_{1j}: The laying thickness of the jth construction area (m);
- h_{2j}: The laying thickness of the jth heavy-duty construction area (m).

$$V_a = \sum_{j=1}^{n} S_{1j}\left(h_{ij} - h_{2j}\right) + \sum_{j=1}^{n} S_{2j}\left(h_{ij} - h_{1j}\right) \quad (1)$$

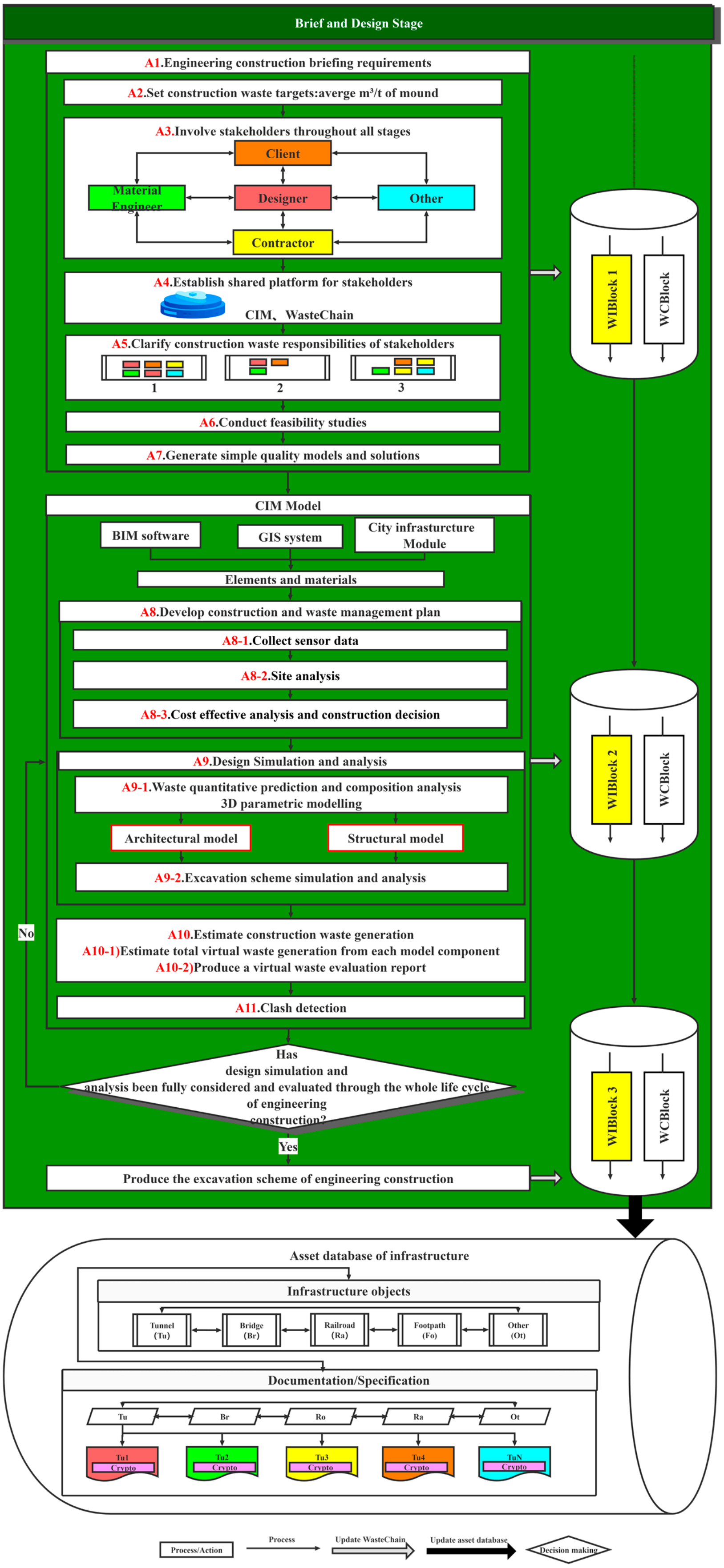

Figure 7. Low-level BeCW framework brief and design stage.

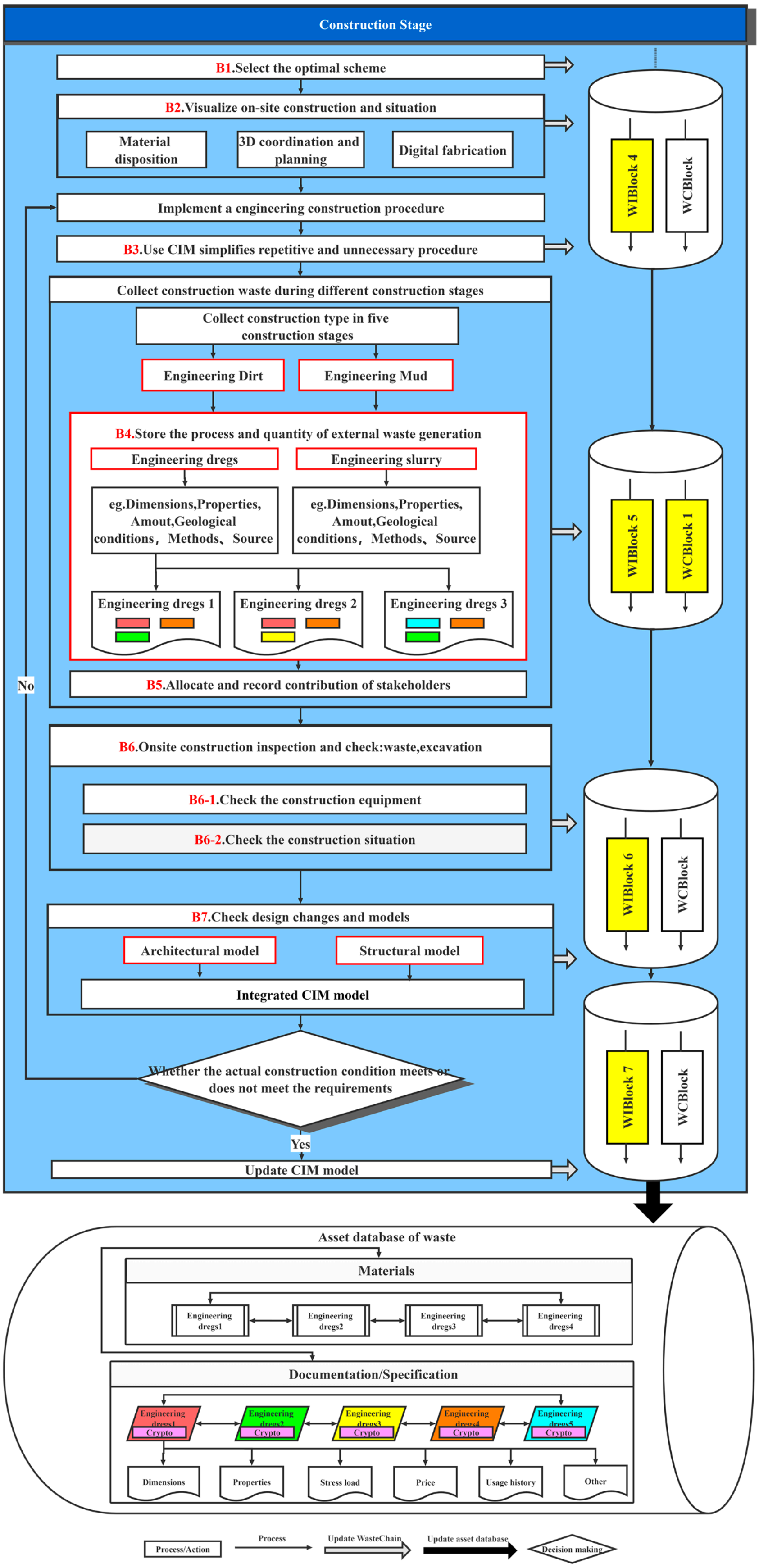

Figure 8. Low-level BeCW framework construction stage.

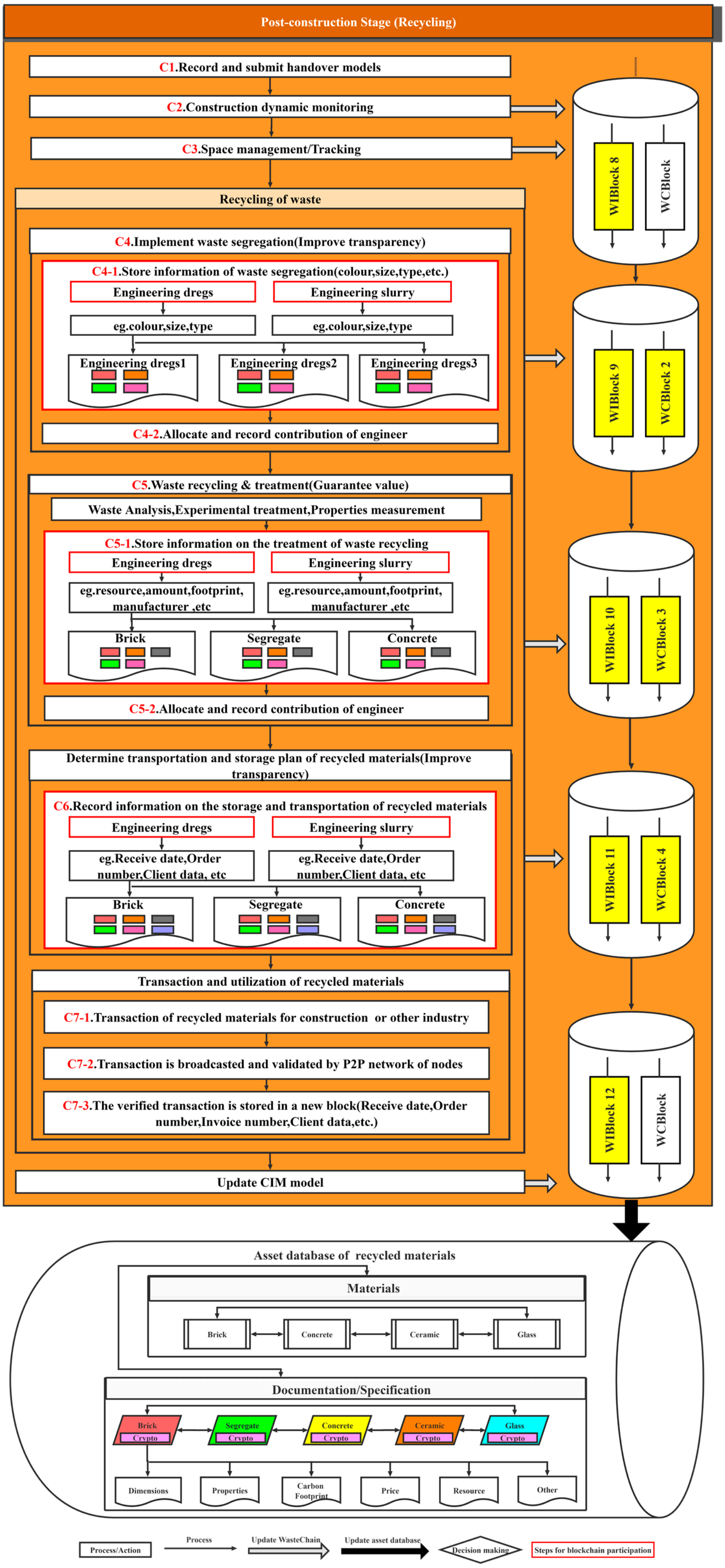

Figure 9. Low-level BeCW framework post-construction stage.

b. Occurrence prediction model where it is impossible to determine whether temporary infrastructure is being constructed at the construction site
1. *A*: the length of the outer edge of the wall in the direction of the length of the building (m)
2. *B*: the length of the outer edge of the wall in the direction of the width of the building (m)
3. *S*: the ground floor area of the building (m^2)
4. *L*: the perimeter of the outer edge of the building wall (m)

$$V_a = (A + 4) \cdot (B + 4) = S + 2L + 16 \quad (2)$$

The asset database of infrastructure contains specifications and CIM objects. CIM objects include buildings, tunnels, bridges, roads, railroads, footpaths, fences, walls, and other objects. The specifications consist of data (i.e., building, tunnel, bridge, road, railroad, footpath, fence, and wall) and file specifications (i.e., Tu1, Tu2, Tu3, and TuN). These data are stored in WasteChain as part of the asset database of infrastructure.

5. Construction stage

The BeCW low-level framework contains correlated actions during the construction stage, as shown in Figure 8. In the construction stage, construction may have an adverse impact on the surrounding environment due to the high technical requirements for construction in certain areas. Using CIM to visualize the onsite construction and situation will reduce the difficulty during construction. After the engineering construction procedure is determined, the CIM platform simplifies repetitive and unnecessary procedures to diminish the loss of manpower and material resources. During the construction process, on-site construction inspection should be conducted, and measures should be taken according to the inspection results. In addition, the occurrence of design changes will affect the construction schedule. Thus, it is necessary to update the data and information in CIM on time and establish architectural and structural models in line with the construction process.

In CWM, the whole construction process is mainly divided into the construction preparation phase, envelope construction phase, main structure construction phase, shield construction phase, and open excavation construction phase. During the construction process, construction waste needs to be recycled according to the different disposal methods, as the quality of the waste is determined by the construction technologies and geological conditions. Furthermore, information about the waste, such as size, quantity, geological conditions, method, source, and the contribution and responsibility of the stakeholders, are recorded on the WasteChain. However, data is susceptible to loss during the exchange process, as such the information is required to be timely uploaded and stored in WasteChain as part of the asset database of municipal waste to ensure the integrity of material information. This asset database of waste consists of specifications and information of various materials. Material types include tunnel muck, engineering residue, and other materials. The specifications contain specific information on materials, such as dimensions, properties, stress load, price, and usage history.

6. Post-construction stage

The detailed improvement measures proposed in the post-construction stage are shown in Figure 9. Construction may cause the destruction, seepage, and deformation of the underground environment. Thus, corresponding measures should be applied to reduce the negative impact on the environment through the real-time dynamic monitoring of construction project data. Space management includes the spatial positioning of construction equipment and hazardous areas, which can be directly visualized via the CIM platform to assist in planning the evacuation route when risk occurs.

In terms of waste recycling processes, blockchain technology encrypted by smart contracts improves the efficiency of the transaction and eliminates the problem of discarding and piling municipal construction waste. Furthermore, the contractor should dispose of the waste in line with the terms of the contract and the policy. If the contractor fails to perform the appropriate duties, the smart contract will be activated and the terms of the smart contract will then be automatically enforced. With the application of blockchain and smart contracts, each stakeholder in the CWM process will be informed about their responsibilities. The BeCW framework constitutes an accountability system that eliminates the problem of unclear waste responsibilities. The responsibility of recycling and the disposal of waste should not only be taken by the contractor alone, but should be shared by all relevant stakeholders involved in the project. In addition, project information can be secured, since the blockchain technology stores information related to waste segregation; treatment of waste recycling; storage and transportation of recycled materials; and transactions of recycled materials at each node at a certain period of time in a separate storage unit. Subsequently, these data are uploaded to the WasteChain as part of the asset database of recycled materials, which consists of specifications and information of various recycled materials. Recycled material types include brick, concrete, ceramic, glass, and other materials. Furthermore, the specifications contain identifiable information on recycled materials such as dimensions, properties, carbon footprint, price, and resource. Finally, automatic and timely information transmission is another benefit for the integration of CIM and blockchain technology.

4.3. The Conceptual Architecture of User Level-Driven Blockchain-Enhanced CWM

The WasteChain and smart contracts help stakeholders to store and verify all information during CWM. Material information before and after experimental processing is stored in the asset database and spans the entire project lifecycle. In addition, the type and quantity of the recycled material, and the means of waste disposal, will affect the price of the secondary materials. Information transparency enhances the fairness of the supply market, eliminates unfair price impacts, and brings benefits to the MCWM of sustainable cities.

In line with the abovementioned potential challenges for adopting the integration of blockchain and CIM for CWM, a respective conceptual architecture of user level in information management is developed, as shown in Figure 10. The conceptual architecture has four levels: user level; application level; service level; and infrastructure data level. From the bottom-up, infrastructure data level consists of the support from Internet of Things (IoT) and big data, and asset database of information. Information and data are collected through IoT and big data, or are obtained from the blockchain. Data are transmitted throughout the CWM process automatically. The service level emphasizes the integration of the CIM knowledge database (i.e., infrastructure module, GIS knowledge database, and BIM knowledge database) with blockchain processor. Service management of blockchain is responsible for managing the CIM and upgrading information in the service level. The application level provides four key applications: peer-to-peer interaction of distributed materials; digital asset security; waste management; and recycling management. These four applications deal with the purpose of data transmission and storage. This draft conceptual architecture emphasizes the value of construction waste and the waste recycling target of sustainable CWM through information exchange in the four layers, which support a transition to circular economy in CWM.

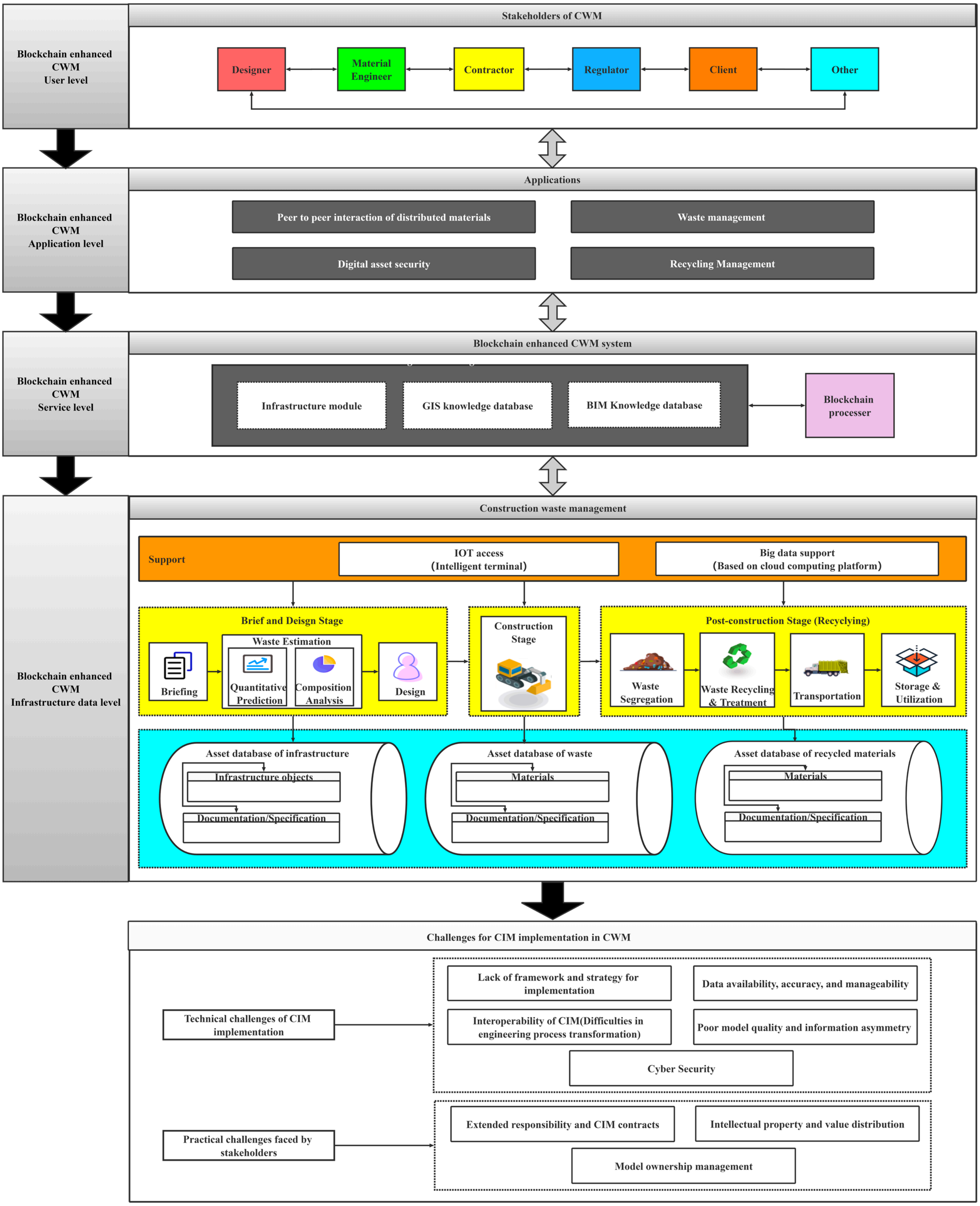

Figure 10. The conceptual architecture of user level-driven blockchain-enhanced CWM in information management.

5. Review and Refinement

5.1. Industry-Reviewed BeCW Framework

The content of the BeCW framework and the draft conceptual architecture of user level-driven blockchain-enhanced CIM for CWM in information management as illustrated in Figures 6–10 have been presented and verified by industry experts and academics at the CSIAM-BTAF 2021 [26]. An industry review of the conceptual BeCW framework was conducted with six industry experts and academics who were asked to use a scale of one–four (one = strongly disagree, two = disagree, three = agree, four = strongly agree) in a pre-interview questionnaire to evaluate the BeCW framework in terms of clarity of structure, comprehensibility of content, and clarity of processes. Table 5 presents the basic information and professional characteristics of the interviewees. As shown in Table 6, all the interviewees agreed that the preliminary BeCW framework was clear.

Table 5. Demographic characteristics of interviewees (n = 6).

Characteristics	n	%
Gender		
Male	5	83.3%
Female	1	16.7%
Occupation		
Industry expert	5	83.3%
University Professor	1	16.7%
Number of years working on blockchain-related research		
Less than 5 years	0	0%
5–10 years	4	66.7%
10–20 years	2	33.3%
Over 20 years	0	0%

Table 6. Mean value of clarity and appropriateness of the BeCW framework by interviewees (pre-interview questionnaire's responses).

Aspects	High-Level	Low-Level
The structure of the framework is clear	3.67	3.67
The content of the framework makes sense	3.33	3.33
The flow of the process is clear	3.50	3.50

The purpose of the follow-up semi-structured interviews was to gauge recommendations on the improvement of the framework. The interviews included general questions about the implementation and use of the BeCW framework, the potential of the BeCW framework to address CIM adoption challenges in MCWM, the feasibility of the consortium blockchain scenario, and the application scope for adding blockchain technology to the CIM platform in the construction sector. All of the interview participants consider that blockchain has a great potential in addressing the challenges of CIM adoption to progress CWM practice. Further, the interviewees provided some helpful suggestions for the improvement of BeCW framework, which include: (1) The WasteChain should be jointly constructed and maintained by multiple parties and stakeholders, including designers, engineers, contractors, sub-contractors, and site supervisors; and (2) standardizing and specifying each component in construction projects as an approach to reduce the construction cost of the consortium blockchain. Subsequently, the original text of the interview was coded using Nvivo11. After the initial conceptualization of the original text, the interview transcript was categorized as five concept nodes that include: strategy issues for implementation; technical issues of implementation; stakeholder issues for implementation; organizational structure issues for implementation; and policy issues related to implementation. By comparing the coding of the interview transcript with that of the other researchers, the percentage of agreement for the coding reliability test was 80%, indicating a high level of agreement in the analysis of the interview material. The coding results, the number of nodes, and the representative texts are shown in Table 7.

Table 7. Coding results of the interview text via NVivo software.

Core Nodes	Number of Nodes	Interview Text (Representative Texts)
Strategy issues for implementation	8	The processing of data in the chain can be standardized, automated, and integrated, and finally forming an intelligent information network
Technical issues of implementation	5	Using distributed management to achieve data consistency, information security, and improve organizational security
Stakeholder issues for implementation	3	Stakeholders in the CIM platform in the blockchain scenario are collaborative and cooperative with each other
Organizational structure issues for implementation	4	Identify the main institutions in the chain, and consider the importance of regulators and cooperation with the government
Policy issues related to implementation	4	Data assetization requires cooperation with government and policy guidance

A further classification analysis of the interview texts (as shown in Table 8) indicates that more industry experts than academics are interested in policy, strategy, technical, and organizational structure issues, which are related to the practical use of the BeCW framework. Interestingly, academics gave more suggestions on stakeholder issues for implementation.

Table 8. Interviewees' suggestions for the BeCW framework implementation analyzed via NVivo software.

Implementation Suggestions	Academics	Industry Experts
Strategy issues for implementation	21.84%	78.16%
Technical issues of implementation	39.8%	60.2%
Stakeholder issues for implementation	76.56%	23.44%
Organizational structure issues for implementation	41.4%	58.6%
Policy issues related to implementation	16.58%	83.42%

In terms of implementation strategies, half of the interviewees suggested that all data in CWM needs to be available from a unified platform, where the data can be standardized and integrated automatically. In terms of implementation technology, one-third of the interviewees believe that the application of the blockchain has increased social trust. However, due to the competitive relationship between stakeholders on the consortium blockchain, light nodes can be introduced to ensure that data is available and invisible. Light nodes store data hierarchically, which avoids the storage problems caused by large amounts of data. One of the interviewees further stated that data should be "collected through sensors to reduce human factors to ensure the integrity, authenticity, and accuracy of data in the consortium blockchain". Among the stakeholder issues for implementation, an industry expert indicated that there may be some small businesses that are reluctant to participate in the implementation of the BeCW framework because this harms some of their interests as a result of limited resources. Thus, the need for incentive mechanisms to enable SMEs to participate in a unified CWM. Half of the interviewees commented on the organizational structure of the implementation of the framework. Due to competing relationships between stakeholders, the consortium blockchain should be built and maintained by multiple parties. Additionally, the importance of regulators is required to be taken into account to ensure that the upstream, midstream, and downstream enterprises are involved. In terms of policy issues related to implementation, more than half of the interviewees suggested that the data capitalization needs to be supported by relevant policies. However, the current policy on data capitalization is still in the exploration stage. Furthermore, most of the interviewees expressed that the government has a responsibility to encourage and support enterprises to apply new technologies, such as blockchain and CIM, to address CWM challenges.

Moreover, the word frequency analysis via NVivo software indicates that, in addition to the topic words such as blockchain, CIM, and waste, other words, namely application, data, management, interests, trust, scenario, cost, copyright, and efficiency appeared frequently in the interviews. The security of data in CWM and the existence of interest relationship between multiple stakeholders attracted the attention from interviewees. Blockchain is suitable for scenarios where multiple stakeholders have competing relationships and priorities. Therefore, the introduction of blockchain into CWM improves the trust between various stakeholders. However, the cost of introducing blockchain technology needs to be considered, and each component of construction projects is required to be standardized to reduce the cost of building a consortium blockchain.

5.2. Refinement of the BeCW Framework

The BeCW framework was updated in line with the improvement suggestions of the interviewees, which include: (1) WasteChain to be jointly built and maintained by multiple parties, including designers, engineers, contractors, builders, and regulators, to ensure the decentralization of the consortium blockchain; (2) Each component in construction projects should be standardized prior to scheme design to reduce the cost of building the consortium blockchain; (3) Adding 'reward mechanism driven value embodiment and information sharing' before the data is transferred to the asset database, which quantifies the work value of stakeholders and motivates the stakeholders to contribute to CWM data; and (4) Adding feedback arrows in the low-level and high-level BeCW framework to link the CIM database to the entire CWM process. As such, the updated high-level BeCW framework, and low-level BeCW framework are, respectively, shown in Figures 11 and 12.

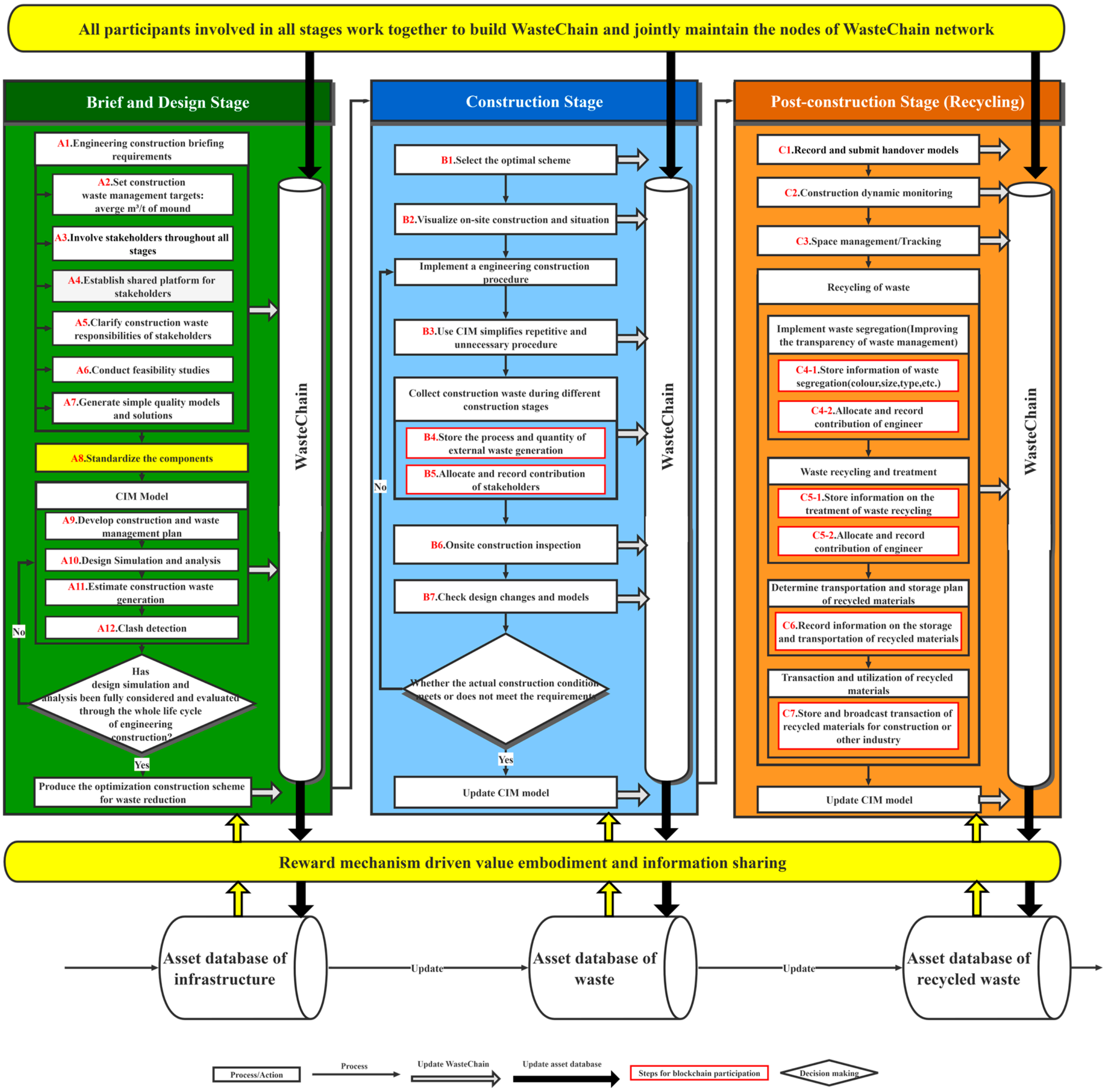

Figure 11. The updated high-level BeCW framework in line with review results.

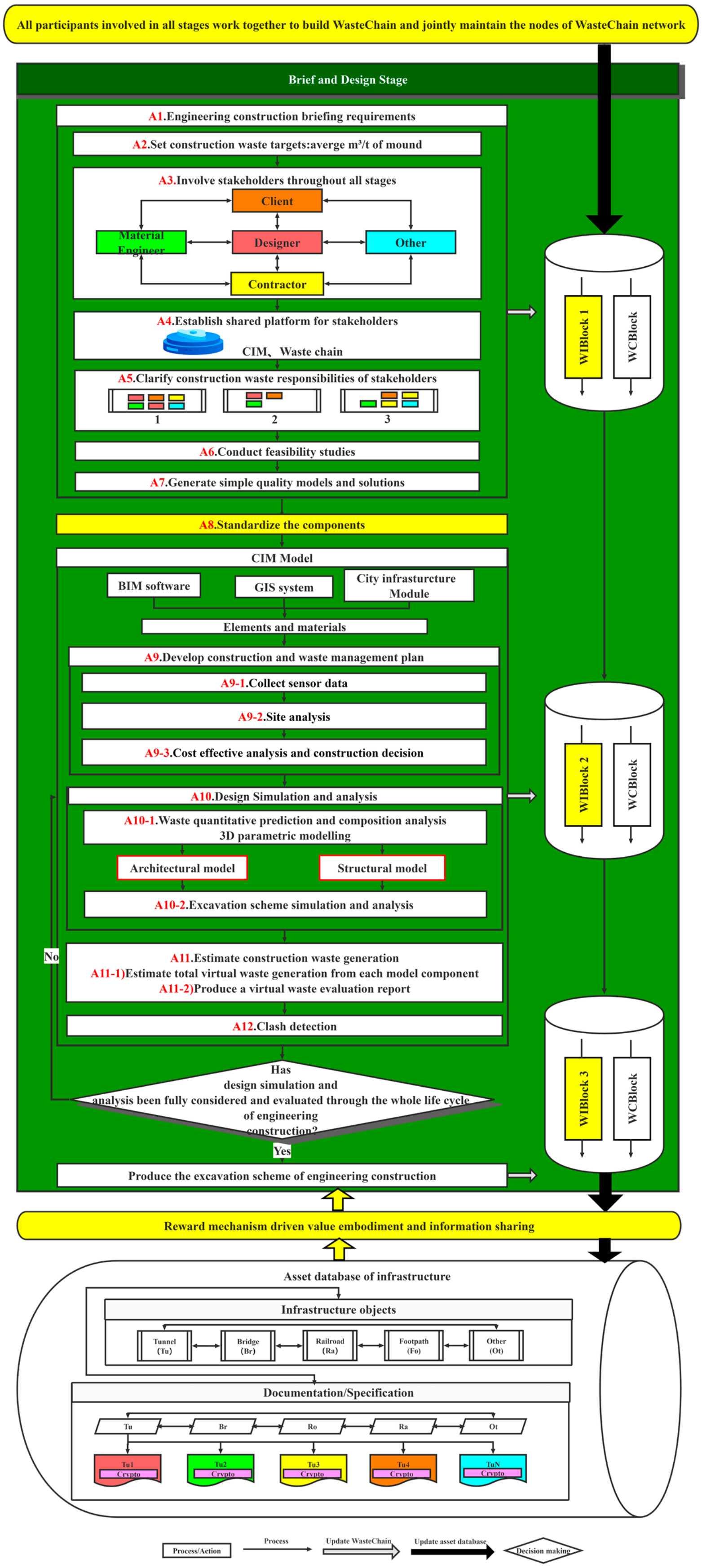

Figure 12. The updated low-level BeCW framework (brief and design stage) in line with review results.

6. Discussion

6.1. Extended Transparency and Traceability of Information and Value Contribution of Stakeholders

The findings of this research indicate that the blockchain has the potential to improve the transparency and traceability of construction materials and waste and identify the value contributions of stakeholders in the process of CWM. The complexity of construction project leads to the difficulty in tracking the status of materials' lifecycles and the responsibilities of stakeholders [48]. In CWM, the exact type, amount, and quality of materials affect the price of materials in the supply chain [100,101]. Thus, the integration of blockchain with CIM alleviates the quality problems, which improves trust between stakeholders [30,81]. Furthermore, blockchain provides the long-term security and traceability of data while creating financial incentives of reward mechanisms which incentivizes stakeholders to be engaged in enhancing CWM process, including waste recycling. In the process of CWM, the decentralized network and consensus mechanism of blockchain quantify the value contribution of the stakeholders. However, different consensus mechanisms will lead to various allocation results. Hence, the future research could concentrate on which type of the blockchain network would be applicable to various construction processes or streams.

6.2. Challenges of Blockchain-Enhanced CIM in MCWM

The implementation of blockchain technology in the construction sector has some limitations. The construction industry is still in the transition to CIM, for which a great deal of time and investment is being spent by companies towards software purchasing, learning, and training. In addition, the cost of employing blockchain can be divided into the network building, deployment, maintenance, and operation costs [81,102]. The complexity of construction projects should be taken into account when constructing the blockchain network. When selecting the deployment of the type of the blockchain network, various criteria should be considered, such as the complexity of the transaction and the applicability for the practical municipal construction case [80,103]. Furthermore, using blockchain in CWM brings additional learning costs [81]. Prior to building a blockchain-enhanced CIM system, stakeholders should determine which information is open for the public, and which information should be kept confidential.

6.3. Theoretical and Practical Contributions

The literature on the potential application of blockchain-enhanced CWM during a building's lifecycle stages points out many advantages, including the encryption of transactions and data, information being transparent to all members, reducing human error, synchronizing transaction information, quantifying intellectual property and value distribution, and guaranteeing the extended responsibility and CIM contracts. However, there is a deficiency of research on the development of tools and methodologies that apply blockchain to support CWM across the building lifecycle stage. Therefore, this paper proposes a conceptual BeCW framework that supports technical staff in the development of related software.

The BeCW framework has been developed to be in line with ITU-T blockchain standard, ISO/TR23244 [20], IEEE blockchain standard [21], JR/T 0184-2020 [22], JR/T 0193-2020 [23], and ISO/AWI TS 23635 [24] for integrated collaboration within CIM knowledge management and coordination database environment. The BeCW framework has the ability to provide a bridge to shift from Level two to Level three, as shown in Figure 13, which could be further enhanced by developing the BeCW framework into a computer program.

The research provides novel insights into the correlation between construction waste causes during a construction project's lifecycle stages and the blockchain potential for improving construction waste information performance. Finally, the BcCW framework could be adopted and customized by other engineering disciplines, such as building energy and water efficiency systems.

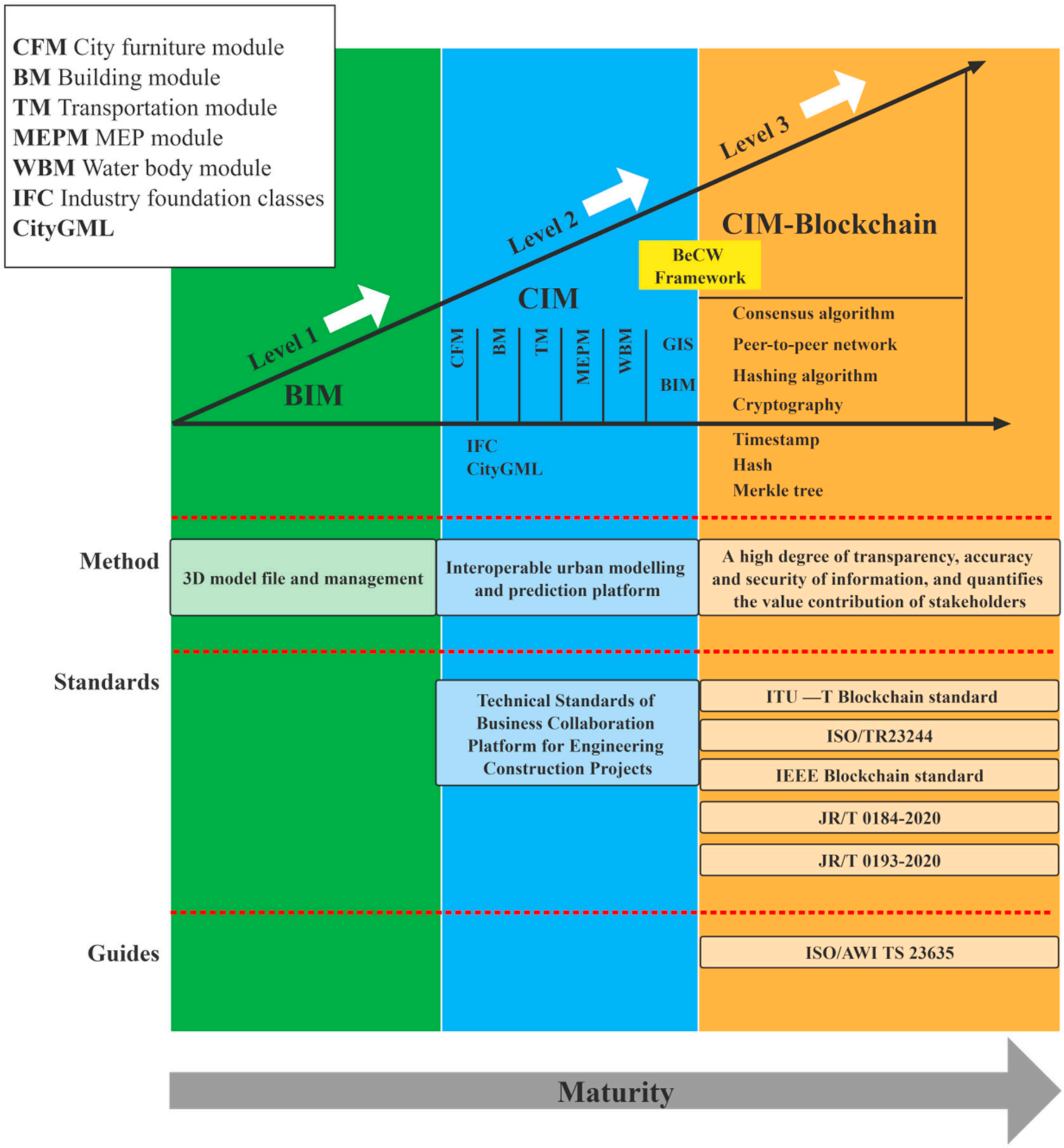

Figure 13. Maturity roadmap of the BeCW framework (devised by the authors based on the literature and the research findings).

6.4. Future Work

Central databases for API and cloud computing could perform similar tasks as blockchain in the CWM. Recent studies have identified the potential of cloud computing in the construction industry, especially in relation to waste minimization and supply chain management [104]. These technologies provide stakeholders with strong computational power for data analysis and rapid and convenient access to construction data. The implementations of blockchain-validation protocols and algorithms such as segregation accuracy, efficiency, user-satisfaction of the BeCW framework implementation, data integrity, transparency, and security, could be investigated, demonstrated and evaluated based on practical scenarios in the future studies.

7. Conclusions

The process of conventional construction waste management requires a lot of paperwork for data recording and the responsibility of stakeholders, which is ambiguous and disputable. The integration of CIM and blockchain can address these problems. However, there are few studies in the field that explore the integration of these digital technologies to address the challenges of a CWM. Furthermore, the current transformative force for the adoption of blockchain technology mainly comes from the mandatory requirements of the government or the pressure from competitors. Technical immaturity, expensive software, and training costs have hindered the implementation of blockchain technology in the construction industry.

This paper examines the current state-of-the-art and existing knowledge on blockchain technology and city information management and their applications in the construction industry to mitigate the existing challenges of CIM adoption for CWM. The blockchain-enhanced construction waste management (BeCW) framework is underpinned by the literature findings. Blockchain has the potential to address the challenges of CIM adoption in CWM, which include the technical challenges of CIM implementation (i.e., lack of framework and strategy for implementation, interoperability of CIM, poor model quality and information asymmetry, data availability, accuracy, manageability, and cyber security) and practical challenges faced by stakeholders (i.e., extended responsibilities and contracts, intellectual property and value distribution, and model ownership management). It plays the role of a stakeholder-driven smart contract accountability system, which helps to record, query, and validate all materials and waste information during a construction project's lifecycle. Subsequently, the BeCW framework and the conceptual architecture of user level-driven blockchain-enhanced construction waste management are verified and refined. The main contributions of this paper can be summarized as follows:

(1) A blockchain-based CWM system is proposed to provide a unified and trustworthy system for evaluating waste recyclability for stakeholders to identify information and aid the decisions process.
(2) A comprehensive methodology that applies blockchain to CWM is proposed to support technical staff in the development of related software.
(3) The BeCW framework is based on the consensus coordination process on WasteChain; waste information can be checked and audited by all consortium members to ensure the record authenticity.

Further, the results of this study could be catalyst for shifting stakeholders' demands towards more recycled materials, as it provides a unified and explicit system for referencing. This paper presents the development of a BeCW conceptual framework, which may require further testing and validation trials for improvement. As such, future work could focus on the framework implementation in specific case studies and the development of associated cost-effective construction waste information management software packages.

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