Reconmatic

Automated Solutions for Sustainable and Circular Construction and Demolition Waste Management

University of Salford

D1.2 Digital Information Management System

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List of Acronyms

Abbreviation / acronym	Description
EC	European Commission
Dx.y	Deliverable number y belonging to WP x
WP	Work Package
DIMS	Digital Information Management System
CDWM	Construction and Demolition Waste Management
CDW	Construction and Demolition Waste
BIM	Building Information Modelling
IoT	Internet of Things
RFID	Radio Frequency Identification
DSR	Design Science Research
CE	Circular Economy
DfD	Design for Deconstruction
ICT	Information and Communication Technologies
MFA	Material Flow Analysis
EoL	End-of-Life
ERP	Enterprise Resource Planning
ML	Machine Learning
LR	Literature Review
ANFIS	Adaptive Neuro-Fuzzy Interface System
WSN	Wireless Sensor Network
FDD	Fault Detection and Diagnostics
BEMS	Building Energy Management System
BAMB	Building as Material Banks
ANN	Artificial Neural Network
BDA	Bid Data Analytics
BPM	Business Process Management

Executive Summary

The construction industry, renowned for its resource intensity, can plate a pivotal role in the Circular Economy (CE) transition. However, the unique industrial characteristics and the intricate nature of CE pose challenges to its implementation in construction. Addressing these challenges necessitates the exploration of Industry 4.0 as promising solutions, given their potential to support decision-making aligned with CE objectives.

The literature is reviewed to identify problems in Construction and Demolition Waste Management (CDWM). Whereas a critical review of the extant literature in the field of Industry 4.0 has established three critical research gaps in the integration of Industry 4.0 technologies to support CDWM. Specifically, the absence of a comprehensive integrative Digital Information Management System (DIMS) covering the entire project life-cycle, from inception to demolition, is an identified key limitation. Information Management involves the procedures through which an organization gathers, organizes, stores, utilizes, and disseminates its data to carry out its fundamental business functions throughout various stages of asset life-cycle activities. Knowing that it is vital in CDWM to understand the generation, composition, flows and recycling potentials. Material flow analysis (MFA) serves as a valuable tool for quantifying material flows and stocks and is widely utilized for this purpose. Most current digital information systems also lack support for MFA. Furthermore, there is lack of clarity of the roles and engagement of various stakeholders within these systems and the CDWM process.

Therefore, this research endeavours to address these identified gaps by proposing the development of a DIMS for Facilitating CDWM, particularly in relation to MFA. This system aims to seamlessly integrates Building Information Modelling (BIM), Blockchain, and the Internet of Things (IoT) to facilitate effective CDWM. The overarching goal is to align these technological advancements with the principles of CE, paving the way for a more sustainable and efficient construction industry, while serving the RECONMATIC demonstrators as pilot applications.

To develop the DIMS, this research adopts the Design Science Research (DSR) methodology. This structured approach commences with an awareness of the problem, progresses to proposing a solution, and involves the iterative development of the artifact through a co-creation between RECONMATIC partners and the wider industry. The subsequent steps include rigorous evaluation of the artifact's effectiveness through the RECONMATIC demonstrators, followed by developing a system architecture and then implement the system architecture in the development of a DIMS demonstrator prototype leading to conclusive findings and informed recommendations. By employing DSR, the research ensures a systematic and practical approach to addressing the challenges in construction waste management within the context of CE principles.

To-date, the study is in the pivotal stage of proposing a solution to integrate BIM, IoT, and Blockchain. This proposed solution aims to address the existing gaps in CDWM by supporting MFA and comprehensively covering the entire life-cycle of a project, while taking into

consideration the role and engagement of stakeholders in the system. This stage of establishing a proposed framework that provides a holistic understanding to the key concepts and constructs, and their relationships, sets the foundation for the subsequent phases of design, development, evaluation, and ultimately, the implementation of an innovative demonstrator solution in the construction industry. With this, the study is poised to advance into the co-creation of the initial system architecture, meticulously designed within the proposed framework developed for the DIMS.

1 Introduction

1.1 Purpose of the document

The construction industry is intricately connected to economic growth, employing approximately 7% of the global workforce and contributing to 13% of the gross domestic product (GDP) (Miller, 2021). However, this industry is also the most resource-intensive in developed nations, responsible for generating approximately one-third of the world's waste and at least 39% of carbon dioxide (CO_2) emissions (Miller, 2021; UNEP, 2019). Furthermore, the unprecedented growth in the global population, particularly in densely urbanized regions, is leading to an exponential increase of 200,000 people daily, all requiring affordable housing and infrastructure. Hence, it is essential to develop urban infrastructure on a scale surpassing what has been constructed in the previous 4000 years to ensure advancements in contemporary and future well-being (Eberhardt et al., 2019).

Consequently, this situation presents a substantial environmental challenge for the construction sector worldwide (Mahinkanda et al., 2023; El Sheikh, 2022; Miller, 2021). Therefore, any effort or initiative aimed at addressing global climate change and promoting cleaner production should encompass this sector (Geng et al., 2017). Another significant concern revolves around the rising costs of raw materials, which compel the construction industry to explore efficient alternative resource materials, such as those achieved through reusing and recycling (Eberhardt et al., 2019; Kylili & Fokaides, 2017). Within this context, it can be inferred that there exists a pressing necessity and substantial pressure within the construction industry to transition from its existing paradigm to a more sustainable one, prioritizing the adoption of a CE approach to promote sustainability within the building sector (Schult et al., 2015; Panteli et al., 2018; Núñez-Cacho et al., 2018).

The concept of the CE, evolved from industrial ecology, aims to consolidate a range of pre-existing ideas from diverse scientific disciplines that share common qualities and features (Jacobsen, 2008). These encompass concepts like industrial ecosystems and industrial symbioses, the 3Rs principle (reduce, reuse, and recycle), cleaner production, including product service system, circular materials flows, biomimicry, cradle-to-cradle design, eco-efficiency, the notion of zero emissions, and more (Díaz-López et al., 2021). The CE paradigm is suggested to alter the current "take-make-dispose" production and consumption model, which poses a threat to the sustainability of human life on Earth and is approaching the planetary boundaries (Rockström, 2009). Progress in this endeavour entails the closure of loops through the reuse of waste and resources, alongside the extension of material cycles by creating durable and reusable products (Ajayabi et al., 2019). The evolution and implications of CE are still in progress (Hossain et al., 2020), and due to its interdisciplinary nature, there is no singular definition of CE (Hart et al., 2019). Given that achieving CE within the construction sector is considered an important objective for national economic growth in many countries (McDowall et al., 2017). Although there are many different CE challenges facing the construction industry, they can generally be broken down into a few key areas of concern, including design and construction methods, supply chain management, policy frameworks supporting CE adoption, end-of-life (EoL) principles, strategies for managing CDW, and information sharing and analytics for CE.

On the other hand, the construction industry is starting to experience the impact of digital transformation and advanced digital tools and methods (Maskuriy et al., 2019). Industry 4.0 technologies are recognised as a critical part of the path towards CE (Singh et al., 2021). With reshaped waste management methods, the combination of industry 4.0 and CE can bring dramatic environmental, health, and societal benefits. The European Commission (European Commission, 2020) identified three areas where industry 4.0 decision assistance systems could potentially assist CE: (1) promoting circular production by tracking, tracing, and mapping resource flows, (2) improving the durability and adaptability of built assets in accordance with CE principles through robust material information management, and (3) innovating data space and providing the architecture and governance system of smart applications. For instance, BIM can be utilized during the construction phase to effectively decrease construction waste (Xu, 2017). Whereas, IoT can improve traceability and real-time visibility of the overall construction processes, enable dynamic decision optimisation, support collaboration and coordination among various stakeholders, and facilitate demolition waste management at the end-of-life (Zhai et al., 2019). Moreover, blockchain has the potential to enhance the accuracy and transparency of on-site construction information, including details like construction logbooks, performed tasks, and material quantities (Wang et al., 2017).

The main reason to implement digital technologies is the aim to increase the speed of decision-making and the management quality of the main business processes (Aleksandrova et al., 2019). The recent advent of new technologies is leading the built environment into a modern data-driven environment. This data driven environment can be described as having five phases based on data utilization criteria: data acquisition, data highway (mobile), data security, data analysis and data realization (Woo et al., 2020; Belle, 2018; Son et al., 2015; Wang, Haider, et al., 2014). This agrees with many authors who studied the utilization of industry 4.0 technologies in construction CE. For instance, Cheah et al. (2022) stated that creating and incorporating new technologies to tackle solid waste problems alone is not enough. Reduction in waste generation deserves significant emphasis. This was supported by the results of many authors who systematically studied the application of industry 4.0 technologies to support the construction CE. However, most of them agree on the importance of integrating these digital technologies that facilitate construction CE implementation, which articulates the complex interrelationships among technologies, business processes, stakeholders, and applications (Yu et al., 2021; Akbarieh et al., 2020; Davila Delgado & Oyedele, 2020; Wu & Gu, 2019; Ratnasabapathy et al., 2019). BIM is an important first step in this transformation (WEF, 2018; UK BIM Framework, 2023). It is crucial to information management because it provides a methodology for structuring data in a way that enables technology to process it (UK BIM Framework, 2023). At its core it represents an intelligent, 3D model-oriented process designed to furnish professionals in the fields of Architecture, Engineering, Construction, and Operations (AECO) with the necessary insights and tools to facilitate more efficient planning, design, construction, and management of both buildings and infrastructure. In a proficiently executing BIM , all involved parties utilize 3D design applications that incorporate comprehensive data on aspects such as project scheduling, cost estimations, sustainability considerations, as well as operational and maintenance requirements. This meticulous approach ensures the accurate and consistent dissemination of information throughout the complete lifecycle of the assets in question, i.e. the *right* information, being delivered at the *right* time, to the *right* people, to make *better* decisions (Casini, 2022; Schweigkofler et al., 2018; Berger, 2017; Boston, 2016).

Furthermore, one of the main barriers for construction waste management implementation is the lack of an efficient information management system (Wuni, 2022). This includes the absence of effective green building design development, limited quality and availability of data (concerns regarding privacy, trust, ownership, and access). Selman & Gade, (2020) also mentioned a lack of documentation for new and used building products, and the scarcity of datasets and tools compliant with BIM standard. This barrier is further corroborated by the British Broadcasting Corporation (BBC), which published a report on '*The big problem of building waste and how to tackle it*' highlighting that the construction industry possesses incomplete, inconsistent data covering materials on construction sites and how they are being used or wasted (Woollacott, 2021). Furthermore, a critical review of the literature on recent studies of digital information systems reveals gaps in the integration of Industry 4.0 technologies to support construction waste management. These gaps include the absence of a comprehensive DIMS that encompasses the entire project lifecycle from design to demolition, a lack of clarity regarding the roles and engagement of various stakeholders within these systems, and the absence of systems that seamlessly integrate real-time data collection, ensure data security, enable traceability and facilitate material flow analysis throughout the entire lifecycle of the project.

Therefore, the research aims to develop a DIMS that integrates Industry 4.0 Technologies such as BIM, Blockchain, and IoT to facilitate CDWM, particularly material flow analysis. This system will address the identified gaps in the literature by providing a comprehensive solution that covers the entire lifecycle of the project, defines the roles of stakeholders, clarifies their engagement within the system, and ensures real-time data collection, and data security. To achieve this overarching aim, the following set of objectives have been defined, a number of which have been achieved, while others are yet to.

1. Establish the problem of CDW, CE principles, barriers, and drivers for implementing waste management practices and roles and engagements of stakeholders within CDW management.
2. Determine the utilisation of Industry 4.0 technologies in CDWM.
3. Identify the current state of art of information management systems, decisions support systems, smart waste management systems for construction and demolition waste CDW based on integrating Industry 4.0 technologies.
4. Develop a conceptual framework for a DIMS that integrates Industry 4.0 Technologies to support 3R principles throughout the lifecycle of a construction project.

5. Evaluate and propose the final framework through RECONMATIC case study, assessing its effectiveness in reducing waste, promoting CE principles, and improving overall sustainability in the construction industry.
6. Design and develop a DIMS system architecture, according to the established framework, and to implement the system architecture in the development of a DIMS demonstrator prototype.
7. To develop recommendations for the implementation of the proposed DIMS framework in the construction industry, including guidelines for stakeholder engagement, data management, and sustainability assessment.

1.2 Structure of the document

The document is structured in 4 major sections.

Section 1 Explores the research background and problem with the research aim and objectives.

Section 2 Presents a comprehensive research literature review.

Section 3 Explains the research methodology followed to achieve the aim and objectives of the research.

Section 4 Presents the work done so far.

Section 5 Conclusion

2 Literature Review

2.1 Introduction

This section delves into the matter of CDW and industry 4.0. It begins by examining where this waste comes from and how it affects the environment. The focus then shifts to exploring the concept of CE, a different way of thinking about waste. The review also considers the factors that make it challenging or straightforward to implement CE ideas in construction. This involves understanding the stakeholders involved. Progressing further, the review critically examines the use of Industry 4.0 in supporting CDWM. Industry 4.0 introduces new technologies that could potentially enhance waste management practices. The evaluation critically assesses how well these technologies' function and their integration into the broader context of waste management in construction.

This critical review of the extant literature was narrowed down further to establish the knowledge gaps in using Industry 4.0 for CDWM. Throughout this exploration of current research, the goal is to piece together the puzzle of CDW problems, CE principles, and Industry 4.0. This literature review seeks to offer insights into existing knowledge and identify gaps for the development of DIMS Figure 1.

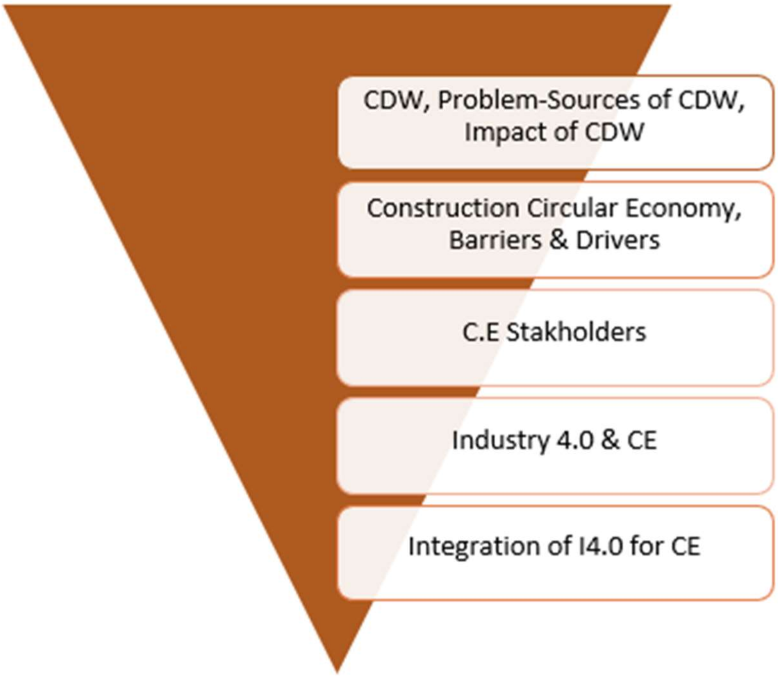

Figure 1 Structure of the Literature Review

2.2 Construction and Demolition Waste

The increasing population and urbanization growth have created significant demand on the construction sector to build a greater number of structures to meet the expectations of both present and future generations (Aslam et al., 2020). The surge in construction activities has led to the generation of a significant quantity of CDW (Menegaki & Damigos, 2018). According to Gálvez-Martos et al. (2018), currently the European construction sector generates 820 million tonnes (megagram, Mg, or 1000 kg) of CDW per year, accounting for around 46% of total trash generated. CDW is produced at various stages of a building's life cycle, including the planning and design phases, due to the insufficient attention given to waste management and waste reduction in the project's early stages (Fritz Benachio et al., 2020). This waste comprises a wide range of materials, including debris resulting from demolitions, renovations, and construction projects, as well as residual waste caused by calamities such as earthquakes and floods (Menegaki & Damigos, 2018). Nonetheless, the most critical stage in the context of CDW generation is the end of a building's life, representing 50% of the total waste generation (Fritz Benachio et al., 2020). This is primarily due to the common practice of disposing of building materials at the end of their life cycle, as they generally lack the potential for reuse (A. Akanbi et al., 2018). The root of this issue lies in the construction industry's reliance on a linear economic model that revolves around the concept of "take, make, and dispose" (EMF, 2015). In this model, the phases embodying this concept commence with the extraction of natural resources from the environment (Mangialardo & Micelli, 2018). These resources are subsequently transformed into construction materials and assembled in the construction site in a manner that cannot be deconstructed, ultimately becoming obsolete upon the end of the life of a building. This necessitates their disposal in landfills or through incineration, along with all the waste generated throughout the entire process (Fritz Benachio et al., 2020; Mangialardo & Micelli, 2018). Therefore, a fundamental requirement for addressing the challenge of (C&D) waste is to gain a comprehensive understanding of its generation, composition, flows and the recycling potentials (Zheng et al., 2017).

2.3 Sources and Causes of C&D waste

In general, Gayakwad and Sasane (2015) classified the sources of CDW into two groups: Small Generators such as small buildings, houses etc. and Bulk Generators such as bridges, roads, malls etc. This categorization was also supported by Badatiya (2015), who noted that the composition of CDW varies depending on the type of structure. According to a study conducted Osmani, Glass, and Price (2008), project design accounts for approximately 33% of on-site waste. Swinburne, Udeaja, and Tait (2010) further highlight that the generation of waste on construction sites can be attributed to various factors, including over-ordering or excessive material quantities, poor handling practices, storage measures and inadequate protection, weak on-site control procedures, inefficient stock control, and damage to materials during delivery. Furthermore, authors such as Polat et al. (2017) provided a more comprehensive analysis of the sources and causes of CDW. They identified a total of 34 factors that contribute to CDW generation, which were further classified into seven main groups. Additionally, Saad et al. (2022) documented these 34 factors in an Ishikawa diagram, visualizing the interconnectedness and relationships between these contributing factors Figure 2.

Furthermore, Fadiya, Georgakis, and Chinyio (2014) explain that construction waste materials originate from multiple sources, including logistics, design phase, and physical construction processes. This implies that the responsibility for waste reduction and environmentally friendly practices should not solely rest on the construction company. Both the client and the designer have the opportunity to make environmentally conscious choices during the program of demands and design stage, contributing to waste reduction efforts.

Referring to previous literature on construction waste, Bossink and Brouwers (1996) highlighted that waste generation often occurs due to design changes during construction, inadequate quality control and assurance, and incomplete documentation for initiating construction activities. Similarly, Lilani Ekanayake and Ofori (2000) emphasized that the factors contributing to waste on construction sites are associated with design, operational procurement, material handling, and site management. Thus, it can be concluded that the understanding of the sources and origins of CDW has remained consistent over the past 25 years.

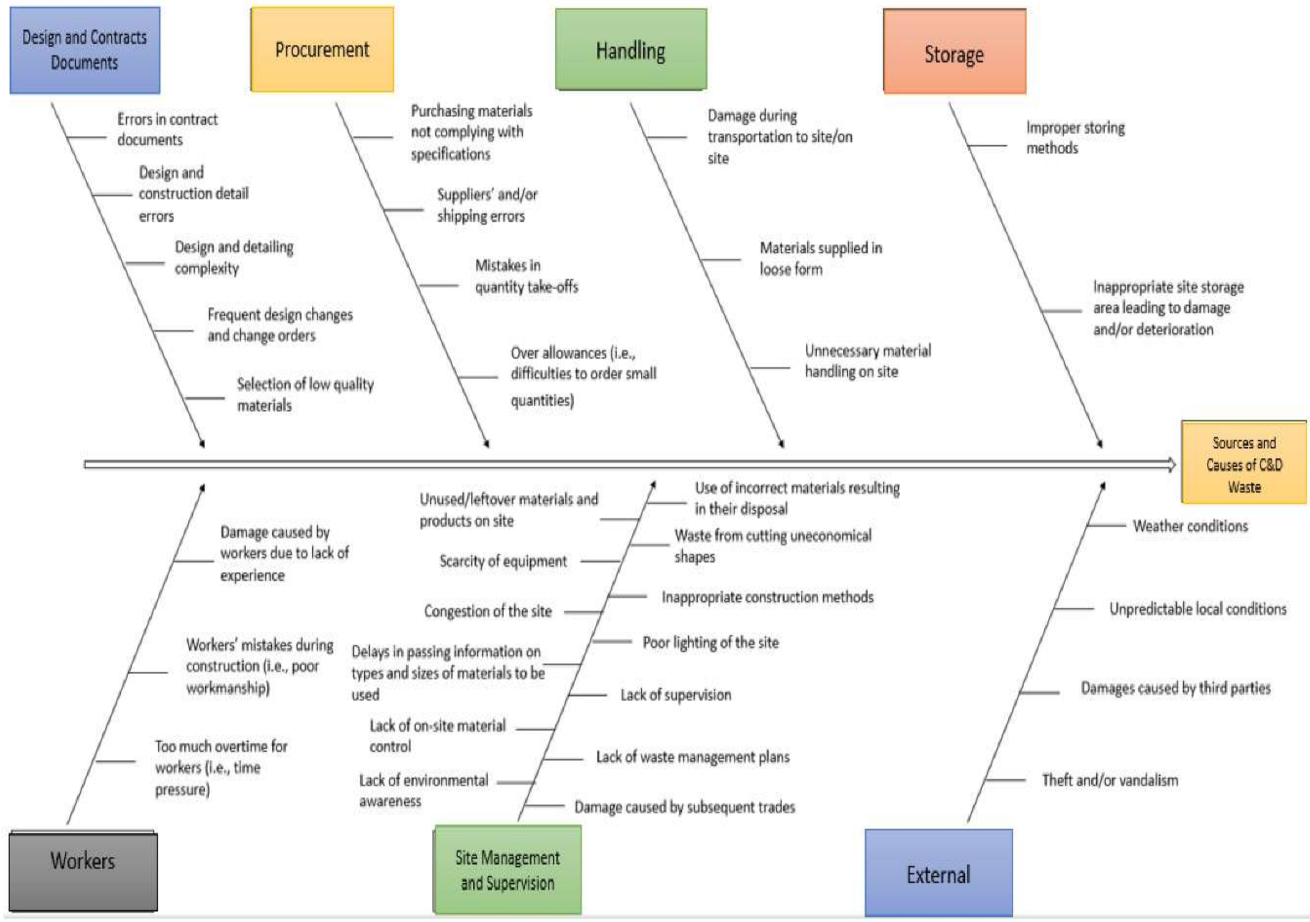

Figure 2 Ishikawa diagram for sources and causes of C&D waste by (Saad et al., 2022)

2.4 Composition of Construction and Demolition Waste

The quantity and makeup of CDW exhibit variations depending on the specific geographical location, which is influenced by factors like population growth, regulatory policies, regional planning, and the characteristics of the local construction industry (Duan et al., 2015). In broad terms, a range of internal factors (e.g. age, building type, construction materials, construction methods) and external factors (e.g. demolition techniques, the waste management capabilities of builders, population growth, etc.) collectively impact both the volume and the nature of CDW generated. (Duan et al., 2015; Chen & Lu, 2017; Polat et al., 2017). Furthermore, according to Nagapan, Abdul Rahman, and Asmi, (2011), construction waste can be categorized into two groups: physical and non-physical waste. Whereas according to GOV.UK, (n.d.), construction waste can be classified into 10 distinct categories. 1. Insulation and asbestos materials, 2. Concrete, bricks, tiles and ceramics,3. Wood, glass, and plastic, 4. Bituminous mixtures, coal tar and tar, 5. Metallic waste, including cable, 6. Soil, contaminated soil, stones and dredging spoil, 7. Gypsum, 8. Cement, 9. Paints and varnishes, 10. Adhesives and sealants. On the other hand, Lu et al. (2016) stated that in Hongkong, the construction waste is divided into inert (soil, rocks, concrete, aggregates etc.) and non-inert (paper, wood, gypsum, drywall etc.) construction waste. Therefore, identifying and quantifying construction waste allows for a better understanding of the waste accumulated at sites. Gálvez-Martos et al. (2018) stated the CDW min and max composition range in Europe (Figure 3), showing that concrete is the most generated construction waste if excavated materials are excluded and is categorized under code 17 01 01 in the European List of Waste, in agreement with a study done by Mália et al. (2013). Other waste classification codes according to the European List of Waste are listed in (Table 1).

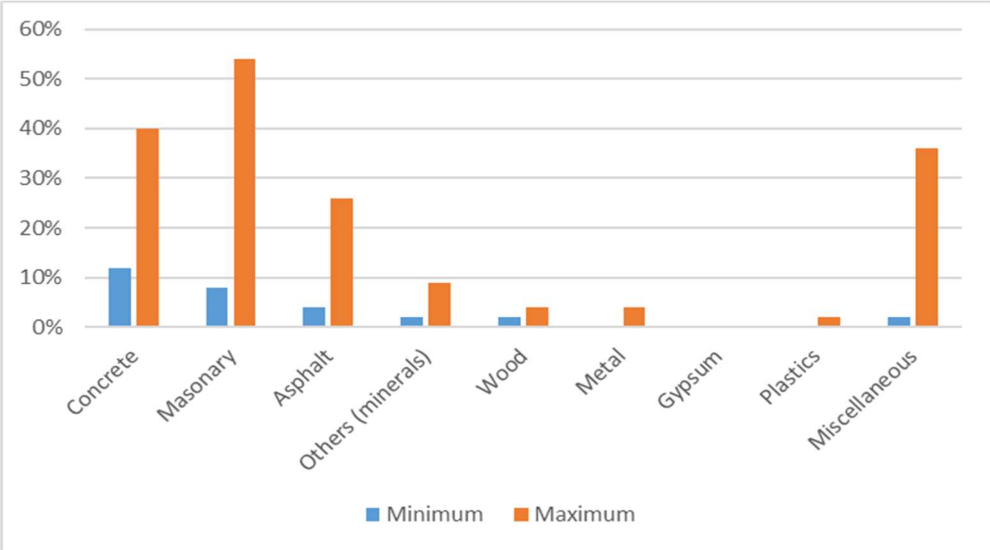

Figure 3 CDW Min-Max Range in Europe (Gálvez-Martos et al., 2018)

Table 1 Waste Classification Code according to (European Commission, 2010)

List of Waste	Classification Code
Non-hazardous	
Concrete	17 01 01
Bricks	17 01 02
Tiles and Ceramics	17 01 03
Mixtures of Concrete, bricks, tiles, and ceramics other than those mentioned in 17 01 06	17 01 07
Track ballast other than those mentioned in 17 05 07	17 05 08
Gypsum-based construction materials other than those mentioned in 17 08 01	17 08 02
Hazardous	
Mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances	17 01 06*
Track ballast containing dangerous substances	17 05 07*
Gypsum-based construction materials contaminated with dangerous substances	17 08 01*

2.5 Impact of Construction and Demolition Waste

The improper management of building materials in construction projects is identified as the primary factor contributing to the generation of CDW (Hassan et al. 2012). Throughout every phase of the construction and building process, the improper handling of waste has led to significant environmental impacts, as highlighted by Begum et al. (2009). In the past thirty years, there has been a growing global concern regarding the impact of environmental pollution on public health, as emphasized by Hossain et al. (2011). Construction activities have repercussions not only on the present generation, but also on future generations. The environmental impact of construction cannot be disregarded, as highlighted by Sa'adi and Ismail (2015).

Inadequate waste management practices emerge as a significant factor contributing to the problem of construction waste. Improper disposal facilities and the absence of clear waste regulations and guidelines serve as the foundation for ineffective waste management, as pointed out by Kimani (2012). Improper disposal facilities and the absence of clear waste regulations and guidelines serve as the foundation for ineffective waste management, as pointed out by Kimani (2012). However, Europe has developed and implemented a myriad of regulations to address this issue effectively. For instance, some of the EU initiatives include the Construction and Demolition Waste Management Protocol and Guidelines for Audits Before Demolition and Level (European Commission, 2021). In the UK, there are specific regulations such as the Waste (England and Wales) Regulations 2011, the Hazardous Waste (England and Wales) Regulations 2005, and the Environmental Protection Act 1990 (Lee, 2022). Nagapan, Abdul Rahman, and Hameed Memon (2012) stress the importance of effective CDW management to prevent adverse impacts on the environment, economy, and society, emphasizing that poor management can lead to problems. However, particular attention needs to be given to construction waste issues that give rise to problems like illegal dumping. Noor et al. (2013) highlights the environmental consequences associated with construction waste, including changes in the environment, disrupted ecological balance, depletion of natural resources potential contamination of sewage systems, and increased energy consumption.

Furthermore, according to a study conducted by Kimani (2012), inadequate waste management practices, including improper handling and disposal of waste, contribute to environmental degradation, risks, and harm to public health. In the context of illegal dumping sites, Nagapan, Abdul Rahman, and Hameed Memon (2012) identify two main factors that contribute to their proliferation. Firstly, the location of construction projects plays a role, as the distance between the project site and the designated landfill may be too far for contractors to transport and dispose of waste effectively. Secondly, financial concerns are also a contributing factor. Contractors may attempt to avoid incurring transportation costs and landfill charges to maximize their profits.

In the context of (CDW) issues, moving to CE is seen as a solution since it will lessen the environmental problems, while also contribute to economic growth (Hart et al., 2019; Hopkinson et al., 2019; Fritz Benachio et al., 2020).

2.6 Construction Circular Economy

The incorporation of circularity is proposed as a crucial aspect for enhancing the sustainability performance of the building and construction industries (European Commission, 2020). There are different definitions of CE (Kirchherr et al., 2017) and there is still no clear accepted definition in the construction industry (Adams et al., 2017). The concept of CE was initially introduced in 2008 through the Circular Economy Promotion Law, enacted by China during the eleventh National People's Congress (Li & Lin, 2016). During its inception in 2010, the Ellen MacArthur Foundation (EMF) played a crucial role in introducing the concept of CE to the global arena. The primary objective behind EMF's discourse was to prompt a reassessment and revival of the pre-industrial practices that aimed to preserve materials and products at their maximum value throughout economic cycles. This vision was advocated as an indispensable alternative for the future of production and consumption, countering the prevailing linear production and consumption model. A major aspect of the discussion centered on the adoption of a new vision for the construction industry (MacArthur, 2013).

The main purpose of waste management is to ensure the preservation of a secure and healthy environment (Demirbas, 2011). This is reinforced by Ghiani et al. (2014) who stress the necessity of well-organized solid waste management as a fundamental responsibility in saving the environment. Additionally, Napier (2016) identified that responsible waste management plays a pivotal role in achieving sustainable construction practices. To accomplish effective management of building-related waste, it requires cohesive efforts and coordinated actions among professionals, businesses, and governmental entities.

In addition to the well-established economic, environmental, and social advantages of waste management, other aspects also stand to benefit. Narcis et al. (2019) emphasize that cost-saving and increased profitability are among the significant benefits of Comprehensive Waste Management. Conversely, another author highlights the positive outcomes of waste reuse and recycling, particularly in terms of cost savings. This observation is further supported by Hwang & Ng (2013), who assert that unnecessary expenses incurred through the purchase of new construction materials can be mitigated by adopting reused or recycled alternatives. According to Narcis et al. (2019), when waste generation is minimized in building projects, it leads to a decrease in disposal costs and landfill charges, thereby effectively lowering the overall project expenses. In effect, these cost savings can subsequently boost project profitability.

Tam et al. (2007) asserted that by minimizing the amount of waste directed to landfills for disposal, the demand for landfills would decrease, leading to a reduction in various adverse environmental impacts. These impacts encompass issues like noise, landfill contamination, and emissions and residues from incineration. Additionally, Hwang & Bao Yeo (2011) indicated that Waste Management (WM) involves not only the monitoring of waste generation but also the planning and control of resources allocated to projects. As a result, improving waste reduction practices and enhancing overall resource management efficiency can be instrumental in achieving better control over resources. Furthermore, precise estimation of the quantities of different types of construction waste in building projects is essential and represents a pivotal factor in the effective management CDW (Li et al., 2016). This is supported by Zheng et al. (2017), who mentioned that a fundamental requirement for addressing the challenge of CDW is to gain a comprehensive understanding of its generation, composition, flows and recycling potentials. Material flow analysis (MFA) serves as a valuable tool for quantifying material flows and stocks and is widely utilized for this purpose. Cochran and Townsend (2010) created a flow chart of where materials enter and leave a structure. Once understood how materials can enter and leave the system, data can be collected by looking at the consumption and disposition of materials by each activity. Hence, the MFA methodology has found extensive use in quantitatively assessing the reuse, recycling and disposal of construction and demolition waste (Dahlbo et al., 2015; Neskovic Markic et al., 2018).

According to Smol et al. (2015), researchers in the CE domain have dedicated efforts to identify the barriers hindering the transition towards CE practices in the context of CDW management.

2.7 Circular Economy Barriers and Drivers

CE initiatives appear to be heading in various directions, like deconstructing design, managing CDW, utilizing secondary materials markets, adopting building information modelling, and exploring urban mining. However, this scattered development and misunderstandings make it challenging to establish a successful CE in this sector (Eberhardt et al., 2020). Additionally, there's a divide between top-down approaches driven by governance and bottom-up approaches involving social movements and innovation. This division raises questions about the roles of stakeholders responsible for the circular transition of the sector (Munaro & Tavares, 2023). Additionally, the sector has unique characteristics related to industry conservatism, complex structures with many interconnected elements (Eberhardt et al., 2020), manufacturing processes, a variety of stakeholders throughout the supply chain, and significant capital investments (Hart et al., 2019). Therefore, several authors focused on studying the barriers and drivers for implementing CE in the construction industry and categorised them. For example, hard factors (technical and economic) and soft factors (institutional and social) were categorised by de Jesus and Mendonça (2018). The challenges were categorised into four levels by Guldmann and Huulgaard (2020): value chain, market and institutional, organizational, and employee levels. Charef and Emmitt (2020) critically reviewed the barriers to implementing sustainable designs and approaches focusing on barriers without drivers. They identified 18 approaches (eg., prefabrication, design for change, design for deconstruction (DfD), reverse logistics, etc.). The common barriers among these approaches were divided into six categories: organizational, economical, technical, social, political, and environmental. Additionally, Munaro and Tavares (2023), the most recent study, categorised the barriers and drivers as economic, informational, organizational, political, and technological.

The focus in this section will be on examining the stakeholders and technological barriers identified in previous studies that hinder the effective implementation of CE practices. Wuni (2022) highlighted Stakeholder Barriers, which encompass various challenges within the CE value chain. These include poor cooperation, collaboration, and communication among stakeholders, leading to a lack of data transparency and information sharing. Additionally, the absence of appropriate partners and participative networks, along with a lack of trust and support among stakeholders, further contributes to these barriers.

Furthermore, Technological Barriers identified by Munaro and Tavares (2023) are crucial aspects of the research. These technological challenges pose significant obstacles to the successful implementation of CE practices. The first set of barriers relates to the lack of integrated CDW processes, tools, and practices. Among these challenges are ineffective CDWM, hindering recycling practices due to limited material separation, logistical constraints, and a lack of processes for producing easily disassembled products (Giorgi et al., 2019). Another challenge is the absence of tools for identifying, classifying, and certifying salvaged materials, coupled with the complexity of materials and building composition due to multiple layers and modifications throughout their lifespan (Ghisellini et al., 2018; Akinade et al., 2019). Additionally, the absence of standardized spatial geometries and limited visualization for Design for Disassembly (DfD) add to the technological hurdles (Akinade et al., 2019).

The second set of technological barriers pertains to the lack of an efficient information management system. This includes the absence of effective green building design development, limited quality and availability of data (concerns regarding privacy, trust, ownership, and access) (Selman & Gade, 2020), difficulties in understanding and developing Environmental Product Declarations (EPDs), a lack of documentation for new and used construction products, and the scarcity of datasets and tools compliant with BIM standards.

On the other hand, the technological driving factors have been identified in previous studies and are instrumental in promoting circularity in the built environment.

One of the key drivers is the adoption of guidelines and tools for circular structures in building and infrastructure sector. Early collaboration and the integration of waste management into project sustainability tools and building control processes have been suggested by Ajayi et al. (2015) as effective means of promoting circularity. Additionally, Ghisellini et al. (2018) emphasised the importance of better resource flow management and the establishment of end-of-waste criteria for CDW at construction sites. Adams et al. (2017) further highlighted the need for the development of symbiosis and enabling technologies to effectively manage CDW.

Incentive design for adaptability and disassembly using tools like BIM has been proposed as a crucial aspect (Ajayi et al., 2015; Hart et al., 2019). Such design tools can play a significant role in promoting circular practices and enhancing the potential for adaptability and disassembly of buildings. Another critical driver for circularity is the establishment of an integrated information system. Tomaszewska (2020) pointed out that improving the certification of recovered materials is essential to reduce uncertainty and build trust in circular practices. Effective and reliable Information and Communication Technology (ICT) solutions are crucial, as emphasized by Aslam et al. (2020), to facilitate seamless information exchange and management within the circular built environment which will be reviewed in the next section.

Moreover, the creation of datasets for BIM and exploring its feasibility for conducting various performance analyses related to resource management is an important step (Chang & Hsieh, 2019). Such datasets and analyses can provide valuable insights and support decision-making processes towards more sustainable and circular building practices.

Understanding these barriers and drivers will be critical in advancing the successful adoption and implementation of CE practices in various industries and sectors.

2.8 Construction and Demolition Waste Management Stakeholders

Effective CDWM necessitates the involvement of numerous stakeholders (Poon et al., 2004; Udawatta et al., 2015). The individuals or organisations involved in CDWM are referred to as stakeholders. Diverse stakeholders have diverse roles, concerns, and goals (Udawatta et al., 2018), which results in different behaviours, awareness, and attitudes (Kim et al., 2020), making implementation difficult. The roles of the stakeholders involved in the CDWM process should be clearly defined (Osmani et al., 2008; Kabirifar et al., 2020). The elements influencing CDWM should be linked to individual stakeholders, allowing them to clearly understand their roles and responsibilities and make more informed decisions during the CDW management process. For instance, Zhao (2021) studied the stakeholder-associated factors influencing CDWM and found 35 factors influencing CDW management linking each factor to at least one stakeholder. For instance, regulatory environment factors such as (sufficient legislation and regulations, enforcement laws, government supervision etc.) are linked to governments. Advances in technologies such as application of information and communication technologies and maturity of the technologies to treat waste are linked to experts, governments, contractors, and recycling companies. Recycling market such as (availability of local waste recycling facilities, supplies of recyclable waste to recycling facilities, demand for recycled products etc.) are linked to recycling companies, contractors, the public and designers. Knowledge, awareness, attitude, and behaviour of stakeholders such as (knowledge and skills of staff, awareness and attitude, top management support etc.) are linked to clients, contractors, designers, and the public. Project-specific factors such as (communication, collaboration and coordination among project participants, formal waste management plans, adoption of low-waste methods in design and construction etc.) are linked to clients, contractors, designers, and experts. However, this study does not consider the reuse market as a factor and the stakeholders linked to it. In addition, it does not address the role of demolition companies, which plays an important role at the EoL as demolition represents more than 50% of the generated waste (Fritz Benachio et al., 2020), and the role of manufacturers/suppliers as it plays a crucial role in promoting CE (Charef, 2022; Honic, Kovacic, Sibenik, et al., 2019). Furthermore, Senaratne et al. (2023) conducted a systematic review of stakeholder collaboration within the context of a circular built environment. The emphasized the significance of stakeholder involvement and collaboration as essential measures for advancing CE in the built environment. The study highlighted various digital technologies, including BIM, IoT, Big Data, and AI, for fostering collaboration among stakeholders in circular processes. However, the study noted that these technologies had limitations in fully promoting circularity. Despite the potential of Blockchain in this regard, there is limited information on its reliability as a technology for enhancing stakeholder collaboration in the context of CE (Senaratne et al., 2023). Therefore, it is important to have a profound understanding of the roles played by stakeholders and how they can collaborate, communicate, and coordinate effectively and securely to implement a successful waste management plan for construction and demolition activities, throughout the whole lifecycle of the project.

2.9 Industry 4.0

In the context of CE, Industry 4.0 technologies such as BIM, IoT, Blockchain, Big Data Analytics, etc. are seen as the main supporters of the CE transition since they initiate and facilitate the implementation of EoL strategy (Uçar, Dain, and Joly 2020). These technologies can transform theoretical CE principles into feasible and practical activities (Antikainen et al., 2018; Garcia-Muiña et al., 2018a; Kintscher et al., 2020). The technologies discussed in this section, namely BIM, IoT, BC, and Machine Learning (ML), have been selected in accordance with the five phases of a data-driven environment (Woo et al., 2020; Belle, 2018; Son et al., 2015; Wang, Haider, et al., 2014), encompassing data utilisation criteria of data acquisition, data transmission, data security, data analysis, and data realisation. Furthermore, these technologies align with and actively contribute to the objectives of this research and the RECONMATIC project, which is focused on the automation of CDW management, CE practices, and data-driven decision-making.

2.9.1 Building Information Modelling

While CE has been growing in popularity, there has also been a global increase in the adoption of BIM. Even though there are varying interpretations of what BIM entails, it has gained significant attention (Charef et al., 2019). Standards and guidelines for BIM implementation have been established in various countries. According to ISO 19650 BIM is '*use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions*' (ISO 19650, 2020). Whereas, according to the UK BIM Framework which also follows ISO 19650, '*BIM plays a key part in the management of information because it provides a methodology that helps us to structure information so that technology can process it*' (UK BIM Framework, 2023). The emergence of BIM necessitates a reconsideration of information flows and communication in building design and construction (Demian & Walters, 2013). It has gained considerable focus in the transition towards sustainable development in the construction industry (A. Akanbi et al., 2018).The planning and design phase is extremely important as it serves as the primary source of information for the entire construction project (Wang et al., 2014). This stage plays a crucial role in regulating the production of construction waste. In general, waste reduction is more achievable during the design phase compared to later downstream stages, as fundamental design choices concerning building materials, architectural technology and other factors tend to have a more significant influence on the quantity of waste produced (Wang et al., 2015). Quiñones et al. (2022) stated that to minimise the generation of construction waste and improve waste management, it is crucial to quantify the waste as early as possible. This necessitates the creation of design-oriented tools that can help forecast the quantity of waste that will be generated during the construction phase. Thus, incorporating BIM during this phase has the potential to transform the design process and facilitate the integration of collaborative and sustainable design approaches (Wong & Fan, 2013; Quiñones et al., 2021; Quiñones et al., 2022). Furthermore, a BIM-based CDW information management system was constructed to facilitate the quantification of greenhouse gas emissions emitted from CDW (Xu et al., 2019). Guerra et al. (2019) presented a software application called WE-BIM Add-in. It is a validated construction waste quantification model that enables waste quantities and types per building element to be predicted in detail according to the European List of Waste and integrated into the Revit workflow. Whereas, Quiñones et al. (2021) developed and designed a BIM-based multiplatform methodology for the estimation of construction waste during building design, as a preceding and essential step for waste minimisation and sustainable management. Cheng and Ma (2013) developed a system to extract material information from BIM and integrated the information into CDW management planning. Miatto et al. (2021) integrated material flow analysis with BIM to track brick material cycles, knowing that it is one of the rare studies which integrated MFA to digital technologies. Furthermore, Honic et al. (2019) created a BIM-based material passport that is employed to assess all materials, including their qualitative and quantitative properties, with the goal of supporting recycling and reducing environmental impacts. In addition, a framework developed by Atta (2021) incorporates Material Passport (MP) into BIM. This integration automates sustainability assessments, while also streamlining the documentation and sharing of building information for future needs.

Proactive planning and management techniques related to building material usage can be implemented through BIM, allowing relevant management personnel to quickly and accurately obtain basic project data. This enables the formulation of precise plans for building materials, which can help prevent resource waste (Kim et al., 2013). To aid in waste management during the construction stage, Bakchan et al. (2019) introduced a multi-dimensional framework based on BIM. This framework can guide the applications of construction waste disposal cost estimation, on-site reuse, and waste bin allocation. Furthermore, Heigermoser et al. (2019) suggested a solution that supports the Last Planner System by utilising the information present in BIM, given the numerous similarities between lean construction and BIM. This tool systematically evaluates and analyses the construction plan to enhance production efficiency and diminish construction waste. Won and Cheng (2017) identified the potential opportunities of BIM to efficiently manage and reduce CDW throughout the entire project lifecycle. The significance of their study lies in the discussion of the roles played by project stakeholders and the information required for each BIM-based approach in CDWM.

Usually, the quantity of debris from building materials that is present at a construction site makes up around 10-20% of the total weight of those materials. On the other hand, the waste resulting from demolishing a building is generally 10-20 times greater in weight than the waste produced during the construction of a new building (Ulubeyli et al., 2017). Typically, CDW is comprised of 70% of waste resulting from the demolition of construction projects

(Martínez et al., 2013). The research suggests that BIM can be significantly beneficial during this phase. For instance, BIM's robust calculation capabilities can be utilised to anticipate the amount of demolition work required and approximate the production of construction waste (Quiñones et al., 2022). According to Nikmehr et al. (2021), BIM also offers the advantage of DfD by altering the design and allowing for the option of deconstruction instead of demolition. For instance, steel structures can be designed using joints rather than welded elements. Wang et al. (2018) carried out a study where they created a theoretical structure by utilizing BIM to aid in evaluating carbon emissions during the entire life cycle of waste generated from building demolition.

In conclusion, the integration of BIM during the planning, design, and construction phases of a project offers significant potential for reducing construction waste and improving waste management. BIM can facilitate proactive planning and management techniques, enabling accurate estimation of waste quantities, resource optimization, and enhanced production efficiency. Furthermore, BIM can support DfD strategies, allowing for more sustainable options such as deconstruction instead of demolition. The incorporation of a MP within BIM, further enhances these benefits by automating sustainability assessments and facilitating the documentation and sharing of building information for future needs. Through BIM'S robust calculation capabilities and the ability to evaluate the life cycle impact of waste, this integrated approach can significantly contribute to the implementation of CE principles in the construction industry, ultimately leading to more environmentally responsible and resource-efficient practices.

2.9.2 Internet of Things (IoT)

The phrase "Internet of Things (IoT)" refers to the interconnected network of physical objects, including devices, vehicles, structures, and other articles, that incorporate sensors, software, and similar technologies such as Wireless Sensor Networks (WSN), Radio-frequency identification (RFID), QR-code, etc.) to establish connections and share data with other devices and systems via the internet or alternative networks (Xu et al., 2014). Such devices can be controlled and monitored remotely, offering the potential to enhance efficiency and productivity across diverse industries (Khanna & Kaur, 2020). IoT stands as a fundamental technology employed to streamline the gathering of spatial-temporal information and aid decision-making within the construction sector. Its application extends to supply chain management, project, and facility management, as well as the monitoring of construction processes (Zhong et al., 2017). Furthermore, according to Ghosh et al. (2020), while research in this area is still in its infancy, the long-term effects of IoT-enabled decision support tools on the CE implementation for the construction industry are anticipated to be significant.

Moreover, Zhai et al. (2019) stated that IoT's abilities to (1) improve traceability and visibility of the overall construction processes, (2) enable dynamic decision optimisation, (3) support collaboration and coordination among various stakeholders, and (4) facilitate demolition waste management at the end-of-life are all examples of how it can help with the transition to CE. A vast amount of construction data could be acquired with the help of an IoT sensing network. However, such data include an extensive amount of implicit information and knowledge, requiring the use of advanced data management systems such as Big Data Analytics (BDA) to explore and make sense for practical activities (Zhong et al., 2017).

2.9.3 Radio Frequency Identification (RFID)

RFID employs various wave frequencies to discern objects. This technology comprises three fundamental elements: an RFID tag, an antenna, and a reader. The RFID tag typically incorporates a microchip for data storage and an integrated antenna that functions as a transmitter. There are two primary classifications of RFID: passive RFID and active RFID, categorized based on their power source. Passive RFID relies on external readers to provide power through wireless communication, while active RFID is equipped with its own internal power source (Lu et al., 2011).

RFID technology finds significant utility within the construction industry by enabling the monitoring and identification of construction materials, components, tools, equipment, and even the workforce. This capability contributes to enhanced productivity and cost-effectiveness in construction projects through efficient tracking and tracing (Iacovidou et al., 2018). A transportation tracking system utilizing RFID technology was created and employed for the purpose of overseeing construction waste management (Ruan & Hu, 2011). Later, systems focused on information life-cycle management, utilising RFID, were suggested to augment control over on-site materials (Lee et al., 2013) as well as to enhance the monitoring and management of materials (Ren & Li, 2018), thereby leading to increased productivity and resource utilization efficiency. Zhang and Atkins (2015) developed a intelligent waste management system that relied on RFID to assist recycling enterprises in tracing, organizing schedules, and addressing instances of waste movement.

Finally, according to Yu et al. (2022), RFID primarily serves to validate the accuracy of material and component placements, furnishing construction managers with immediate insights into the quantity and timing of material deliveries. It also finds utility in enhancing material consumption efficiency from three perspectives: (1) tracing delivery logistics to minimise waste generation, (2) facilitating interchangeability and adaptation for new purposes during renovation, and (3) managing their condition and performance throughout operational and end-of-life phases.

While numerous studies have concentrated on utilizing RFID for tracking and tracing construction materials and components, there remains a dearth of research when it comes to who is responsible to develop RFID for tracking and tracing construction products.

2.9.4 Blockchain

Blockchain, as described by Wang et al. (2017), functions as a technology for decentralised management of transactions and data. It establishes a decentralised framework in which the management, execution, and oversight of transactions are not dependent on trusted intermediaries, as noted by Yli-Huumo et al. (2016). Therefore, the utilisation of blockchain holds the potential to considerably diminish the burden associated with transactions (Ølnes et al., 2017). While both BIM and Big Data can serve as methods for data communication, it is worth highlighting that (BC) stands as the singular technology that employs decentralised record databases, allowing network participants to engage in direct interaction through a peer-to-peer network for purposes of sharing information and conducting payment transactions, as emphasized by (Turk & Klinc, 2017).

Moreover, Wang et al. (2017) stated that blockchain has the potential to enhance the accuracy and reliability of on-site construction information, including details like construction logbooks, performed tasks, and material quantities. The distributed nature of (BC), such as its decentralised nature and key features like transparency, immutability, and traceability, offer a promising avenue for addressing challenges in historical waste data quality, reporting, and overall data management. Despite these capabilities, the utilisation of blockchain technology within the broader construction sector remains limited, and there is a scarcity of research investigating its specific role within the waste management aspect (Turk & Klinc, 2017). Wilson et al. (2023) developed a multi-blockchain system to create MPs. These passports track the history and provenance of construction materials and can be used to support product recycling in the construction sector.

Furthermore, blockchain possesses the potential to fundamentally alter the conventional methods of gathering, storing, duplicating, and tracking waste data during every stage of waste movement. This transformation allows for the evaluation of waste management effectiveness while meeting regulatory requirements. Operating as a transactional tool, it has the capability to streamline the trading of CDW, enhancing operational effectiveness, trustworthiness, and clarity by directly linking waste producers and consumers without the need for an intermediary of trust (Ratnasabapathy et al., 2019).

2.9.5 Machine Learning & Artificial Intelligence

Artificial intelligence (AI) is the capacity of a machine to carry out certain cognitive tasks that humans typically connect with minds (McKinsey, 2023). According to Talla and McIlwaine (2022), proficiency in AI capabilities can contribute to tasks such as design, enhancing infrastructure efficiency, and effectively managing circular business models. These competencies collectively support the shift towards CE. In CE, ML finds application in facilitating the optimisation of processes and systems by harnessing vast volumes of data. Weichhart et al. (2016) argue that the adoption of AI methodologies in the development of intelligent enterprise systems signifies a significant leap in computing theory and applications, particularly in the context of circular business models. Additionally, to help architects in the early design stage, researchers developed and tested a ML model that can anticipate the entire carbon footprint of different regenerative building designs (Gan et al., 2020). Whereas, researchers underline the potential of machine learning algorithms to forecast buildings' energy use (Mehmood et al., 2019). A practical instance is the FaSA project (Façade Service Application), which maps the current state of buildings and predicts the maintenance needs of the façade components using AI, drones, and sensor technologies (Akanbi et al., 2020). Additionally, AI methods are also important for activities in the end-use phase of a building. In order to calculate the amount of waste products obtained from deconstruction and demolition activities, Akanbi et al. (2020) developed current neural networks based on national demolition data. Whereas, using machine learning approaches, Rakhshan et al. (2021) created a prediction model for estimating and evaluating the reusability of structural components. Furthermore, Davis et al. (2021) developed an on-site waste grading system based on digital photographs collected from worksite containers that can categorise different sorts of trash using a classification algorithm.

The scholarly discourse on the application of Industry 4.0 principles within the realm of construction CE has been characterised by a prevailing consensus regarding a notable deficiency in the integration of digital technologies. Numerous academic articles dedicated to exploring this integration have concurred that a significant gap exists, manifesting as the need to seamlessly incorporate an array of digital tools and systems into construction processes. These tools encompass decision support systems, smart waste management systems, and smart circular systems etc. Researchers recognise that these digital technologies play a pivotal role in enhancing the efficiency, sustainability, and overall efficacy of construction CE practices. Consequently, the overarching sentiment within the academic literature underscores the imperative to address and bridge this gap by fostering the integration of these advanced digital solutions into the construction industry's circular economy initiatives (Table 1). The next section will provide an overview of previous studies that have examined the integration of Industry 4.0 technologies in the construction sector. In particular, these studies consistently highlight the crucial gap in incorporating digital tools such as decision support systems, smart waste management, and smart circular systems etc.

Table 1 Future recommendations for Industry 4.0 technologies in CDWM

Future Recommendations	Authors
Provide compatible data management support to enrich regional data sources of CDW and enable accurate data-driven decision supports	(Yu et al., 2022; Akbarieh et al., 2020; Davila Delgado & Oyedele, 2020; Demestichas & Daskalakis, 2020)
Integrate smart technologies to aid the waste data management, waste quantification, auditing and waste diversion in the C&D Sector	(Yu et al., 2022; Li et al., 2020; Ratnasabapathy et al., 2019)
Integrate 3R Principles in different life-cycle phases and Innovate CE Business Models Linking Construction and Demolition in broader business ecosystems	(Demestichas & Daskalakis, 2020; Akbarieh et al., 2020; Wu & Gu, 2019)
Improve Interoperability of processes & data	(Akbarieh et al., 2020;Davila Delgado & Oyedele, 2020; Demestichas & Daskalakis, 2020)
Introduce new technologies or methods into this field. For example, block chain technology can be applied to explored in aspects of life cycle information monitoring, supply chain traceability, incentive mechanism construction, etc.	(Wu & Gu, 2019)

2.10 Integration of Technologies

In the dynamic landscape of technological advancements, there exists a significant research gap in integrating Industry 4.0 technologies to support CDWM effectively. This gap is particularly evident when examining the fusion of Industry 4.0 technologies, including BIM, ML, Blockchain, IoT, and sensor technologies, in addressing this critical aspect of the construction process (Yu et al., 2022; Elghaish et al., 2022).

While various studies have explored the integration between these technologies, their application to waste management is an area that requires more attention. This section serves as a call to explore how these powerful tools can be connected to optimize waste practices, trace materials, track waste efficiently, and enhance sustainability within the construction and demolition sectors.

2.10.1 BIM and Machine Learning

In recent years, the combination of BIM with ML has come to be seen as an effective method for transforming the AEC sector. BIM as a digital representation of a building's structural and functional characteristics, and ML with its ability to analyse vast amounts of data and identify patterns, have combined to improve decision-making, optimise project management, and boost overall project outcomes. Professionals in the AEC industry can gain useful insights, forecast performance, and automate various processes, by leveraging BIM and ML techniques and algorithms. This results in higher productivity, cost savings, and sustainable solutions (Zabin et al., 2022; Su et al., 2021; Hu & Castro-Lacouture, 2019; Lin & Huang, 2019; Lomio et al., 2018; Ustinovichius, et al., 2016).

According to a systematic study conducted by Zabin et al. (2022), most of the research on the integration of ML and BIM has primarily focused on the design phase. Furthermore, the integration has also been explored in other domains, including evacuation and disaster management, model and data classification. Although the construction phase has garnered significant attention following the design phase, researchers have increasingly recognised the relevance of ML and BIM integration in the operation and maintenance phase. Notably, the study did not explicitly address the application of this integration within the demolition phase.

In terms of design, Zabin et al. (2022) and Ustinovichius, et al. (2016) studied the integration between ML and BIM for planning and design automation Zabin et al. (2022) studied an application of ML to the construction industry and used classical and modern ML methods to categorise images of building designs that are extracted from BIM which are used to store building designs. Whereas, Ustinovichius, et al. (2016) developed a spatial planning model for buildings associated with a territorial planning system. Furthermore, Hu and Castro-Lacouture (2019) and Lin & Huang (2019) studied the integration for clash detection where this is very critical in reducing construction waste (Han et al., 2021). Hu and Castro-Lacouture (2019), integrated BIM and ML to improve the quality of clash detection by supervised algorithms that are used to automatically distinguish relevant and irrelevant clashes. Lin and Huang (2019) developed a method that automatically screens for irrelevant clashes by combining supervised machine learning and rule-based reasoning. Moreover, for analysing design productivity Pan and Zhang (2020) developed a clustering-based BIM log mining method to provide a data-driven knowledge discovery about the design productivity characteristics from a huge amount of BIM design log data. Nevertheless, Lee et al. (2019) proposed a design support system, using automation rule checking to identify the compliance of rules and adopting case-based reasoning to provide recommendations via ontology and semantics.

While several articles individually explored BIM and ML for CDW prediction (Lu et al., 2021; Yang et al., 2021; Ahmed & Asadullah, 2020; Akinade et al., 2018), only a limited number of articles developed predictive models for waste analytics based on the integration of BIM and ML. Alshibani and Alshamrani (2017) developed a conceptual system that incorporates 3D BIM and an ANN-based model to predict energy cost and help architects in selecting the optimum alternative design that minimises the cost of energy consumption of residential building. Moreover, Akinade and Oyedele (2019) developed a BIM-based computational tool for building waste analytics. The construction waste prediction model was developed using Adaptive Neuro-Fuzzy Inference System (ANFIS) and added into Autodesk Revit BIM platform. This focused on the importance of developing in the future a BIM-enabled CW collection tools, which will integrate waste data records into BIM models. This shows that there is a need for real time data collection tools, to collect the actual data of the generated waste.

2.10.2 BIM & IoT

Real-time data from IoT devices integrated with BIM gives an effective paradigm for applications to increase construction and operational efficiencies (Tang et al., 2019). The development of IoT is based on BIM (Yu et al., 2022). BIM models offer a high-fidelity operable dataset that captures the building objects, attributes, and spatial organisation as a set of virtual assets by including geometry, spatial position, and a scalable set of metadata properties. The real-time and recordable status from the actual operations in construction and operations provided by IoT data enhances this data collection (Tang et al., 2019). Furthermore, according to research in the built environment, traditional silos can be broken by IoT throughout the entire lifecycle, from design to construction to handover (Dave et al., 2018). Previous research has incorporated BIM and IoT devices across various domains, including energy management, construction monitoring, health and safety oversight, and building management (Tang et al., 2019).

A BIM platform empowered by IoT was created with the objective of improving real-time transparency and trackability within the supply chain of prefabricated construction. This innovation holds promise in reducing waste production by delivering services for production and transportation planning (Zhong et al., 2017). Furthermore, the integration of BIM and IoT facilitated precise data gathering, prompt information sharing, and automated decision support across the entire lifecycle of modular construction endeavours (Zhai et al., 2019). In a similar vein, a corresponding approach was employed to create a BIM system grounded in the principles of the Physical Internet. This system effectively gathered and transmitted real-time project information, thereby enhancing energy efficiency in the domain of prefabricated construction (Chen et al., 2017). Whereas, Xu et al. (2023) developed an embodied carbon monitoring system for prefabricated buildings by integrating BIM and IoT. This developed system is comprehensive in the development of the IoT-BIM integration where it lacks in the collaboration and role of stakeholders in implementing it. The review of the integration of Building Information Modeling (BIM) and Internet of Things (IoT) components is discussed in the next section.

2.10.2.1 BIM & RFID

The integration of BIM and RFID technologies has emerged as a promising solution to enhance construction industry practices, enabling efficient data management, improved project coordination, and enhanced productivity. Furthermore, the integration of RFID and BIM systems has emerged as a promising approach for promoting CE principles in the construction industry, enabling effective materials tracking, waste reduction, and resource optimisation throughout the building lifecycle. For instance, Hossain and Thomas (2019) studied an approach for adaptable buildings through the ownership reassignment of movable components, supported by RFID technology and BIM. This study demonstrated the possibility of connecting data related to physical component via RFID tag and the reader to a BIM, including the virtual component. However, the research gap in this study pertained to the seamless integration of Cloud-BIM-RFID which presents an opportunity as an information management platform to facilitate efficient storage and retrieval of building information, in addition to defining the role of stakeholders in this integration. The importance of connecting BIM to the cloud, mentioned by Chen et al. (2016) is evident. Cloud-based BIM offers end users universal access to data, enabling real-time collaboration among project stakeholders across the globe, while reducing hardware requirements through high-collocation data centers. Nevertheless, recent attention has turned to the drawbacks of cloud-based BIM systems. Operating within a centralised data center, these systems come with inherent risks, notably the potential for data loss in the event of server node failure without adequate backup measures in place (Wong et al., 2014). Furthermore, the vulnerability of data stored in the cloud to unauthorized changes or deletions, as mentioned by Ho et al. (2017), underscores the necessity for robust and trusted network infrastructure for data storage and computing. This shows the importance of having Blockchain as a decentralised database to facilitate the secure and private sharing of this data, ensuring robust privacy, security, and scalability measures (Zhang et al., 2023; Elghaish et al., 2021).

Moreover, Copeland and Bilec (2020) focused on exploring CE strategies and principles for Building as Material Banks (BAMB) projects, as well as examining the existing methods connecting demolition and construction projects. It investigated the potential of technologies such as BIM, RFID data tag, and blockchain to facilitate these relationships and proposes a framework that integrates both past and present technologies. This research gap lied in the absence of a case study to accompany the theoretical framework, process flow model, and visualisation of the integration process.

Furthermore, Swift et al. (2015) explored the integration of BIM and RFID tags to enable the reuse of building components and reduce waste, energy consumption, emissions, and costs.

The research examines the feasibility of exchanging data between BIM and RFID technology and highlights its potential for efficient identification, tracking, and management of building components throughout their lifecycle. This research was limited in empirically validating the decision support by using real data. This shows that there is a common research gap in both Copeland and Bilec (2020) and Swift et al. (2015).

Several scholarly articles have explored the synergistic potential of integrating RFID and BIM technologies to enhance construction management practices, facilitating real-time tracking of resources, improved project coordination, and efficient decision-making processes. Abbott and Chua, (2020) proposed a framework that demonstrates the advantageous outcomes of integrating RFID and BIM. The integration established a robust basis for optimising various facets of the construction, delivery, and installation of Prefabricated Prefinished Volumetric Construction units. By this, the framework enables analysis of production efficiency and facilitates improvements in workflow efficiency. This integration enhances the accuracy of assembling components with their intended modules, leading to positive outcomes in the construction process. However, the study did not consider the whole lifecycle of the project. Giusti et al. (2020) employed an integrated approach that incorporated BIM, RFID, and cloud server technologies to track metallic forms for the cast in place wall reinforce concrete system throughout the construction process. Notably, the author's primary emphasis was on tracking the formworks, rather than solely focusing on the construction components or construction waste. This can be taken as a foundation for integrating these technologies to track materials and waste in operation and demolition phases of the project.

On the other hand, Wu and Liu (2020) departed from conventional studies by employing a unique approach that entailed the integration of BIM and RFID for the purpose of effectively managing the lifecycle of prefabricated buildings encompassing the planning and design phase, prefabricated component production stage, site construction stage, and operation and maintenance stage. Notably, the study omitted the demolition stage from its scope. Furthermore, the research did not incorporate a cloud-based platform for the integration of BIM and RFID, which could have potentially enhanced data storage capabilities.

The articles mentioned above collectively provide valuable insights into the integration of BIM and RFID technologies in various aspects of the construction industry. However, there are several research gaps that have been identified. These include the need for seamless integration of Cloud/BC-BIM-RFID to enhance data storage and management. Additionally, the absence of case studies limits the validation and practical application of proposed approaches. Further, empirical validation using real data is necessary to demonstrate the actual benefits of integration. Lastly, the coverage of the full project lifecycle, including the demolition phase, is lacking in some studies. Furthermore, it is noteworthy to mention that none of the articles discussed the utilisation of RFID and BIM integration specifically for managing and addressing construction and demolition waste generation. This area remains an important research gap, as RFID and BIM technologies have the potential to enhance waste tracking, analysis, and optimization throughout the construction process. Future studies could explore this aspect to develop smart solutions for sustainable waste management in the construction industry.

2.10.2.2 BIM & QR Code

The combination of BIM-QR has the characteristics of low investment, flexibility, and convenience. As the utilisation of smart devices grows and QR code technology gains more traction, the potential of QR code in the construction industry has been gradually explored (A. Yavuz Oruc et al., 2021). Whereas, it has been found the research in this area is still limited. For example, Pavan Meadati and Irizarry (2015) used this integration for the Operation and Maintenance phase of the project, where they mentioned that this integration creates an automated environment that streamlines the process of identifying and selecting elements within BIM. This integration facilitates a smooth exchange of information between physical objects and BIM elements. By automating these tasks, the system significantly cuts down on the time required for identification and selection, while also minimizing the occurrence of manual errors. Moreover, the BIM & QR environment synchronises dynamic user input, thereby enhancing the efficiency of information retrieval. Given the increasing prevalence of smart device users, the BIM & QR environment holds the promise to usher in a transformative era in the realm of Operation and Maintenance (O&M) (Pavan Meadati & Irizarry, 2015). Moreover, a system was created by Lorenzo et al. (2014) utilising BIM-QR-code integration to enhance the quality of design and the management of the construction process in the execution phase. This innovation improved the communication among the client's technical structure, the contractor, and subcontractors, resulting in improved accessibility to on-site health and safety documents and information. Furthermore, Vasilyev et al. (2019) studied the interaction of BIM and QR-codes on a construction site. The study demonstrates the incorporation of QR technology into construction management, enhancing data availability and collaboration. This entails an Internet of Things (IoT) integration solution involving mobile QR-code exchanges, aiding construction monitoring and staff control via smartphone scans and "smart scanners." The approach suggests application potential for an integrated Enterprise Resource Planning system within the IoT framework. Finally, Hao (2022) created an assembly building information management method by this integration, mentioning that by this integration BIM software advances building information management, fostering industrialisation. Standardised design and QR-coded components aid prefab construction. The process, using codes and QR tech, enables a comprehensive BIM model, tackling information isolation in prefab design, production, and construction. It achieves intelligent, visual management across design, production, transportation, and installation.

2.10.2.3 BIM and Sensors

Numerous authors have explored the integration of BIM & Sensors in their studies. Liu et al. (2018) mentioned by his systematic study that previous publications focused on integration methods for integrating BIM & Sensors, operation and maintenance, sustainability, positioning and tracing, structural health monitoring, and planning and design.

The integration approaches centre around selecting appropriate sensor types, determining their strategic placement within the building, and effectively integrating BIM with sensor-acquired data. This encompasses data processing, analysis, and presentation techniques (Liu et al., 2018). Brilakis et al. (2010) introduced an automated algorithm that creates parametric BIM models through the utilisation of data obtained from LiDAR (Light Detection and Ranging) or photogrammetry. The algorithm categorises building material prototypes, shapes, and their interconnections. Subsequently, it identifies specific elements from the classification that align with distinct visual criteria. Modelers are primarily tasked with model verification and the treatment of specific elements. Based on this, automated technique was proposed by Lagüela et al. (2013) for producing textured models. In a different approach, Xiong et al. (2013) presented an integration method that involves learning surface attributes of distinct elements and establishing contextual connections among objects. These elements are subsequently categorized into walls, ceilings, or floors, allowing for thorough analysis and precise identification of surface openings.

Whereas, with respect to sustainable buildings in most studies two themes were found for integrating BIM and Sensors: energy consumption and environment protection. A wireless sensor network (WSN) is developed by Woo and Gleason (2014) to gather diverse records concerning energy consumption within buildings. Subsequently, this data was harnessed to support building retrofit design in conjunction with BIM. In contrast, Dong et al. (2014) focused their endeavors on creating an integrated system for Energy Fault Detection and Diagnostics (FDD), where they combined a Building Energy Management System with FDD and BIM elements in order to improve energy conservation. A Wireless Sensor Network was implemented by Wu et al. (2015) to oversee energy usage in data centres. They integrated BIM to anticipate the real-time thermal conditions in server work environments. By contrasting predictive results with historical data, operators swiftly identify thermal hotspots and implement interventions to enhance energy efficiency. Furthermore, within the environment protection, Howell et al. (2017) emphasised the prudent utilization and preservation of natural resources. They integrated sensor networks and BIM to observe water resource consumption, ultimately creating an intelligent management system for the astute administration of water resources. Similarly, Mousa et al. (2016) focused on addressing carbon emissions stemming from buildings. They forged a quantitative link between carbon emissions and data related to energy and natural gas consumption, which was obtained through sensors. By incorporating BIM, they devised a carbon emission model that aids in the management of carbon emissions and facilitates pertinent decision-making.

Moreover, the use of BIM-Sensors in the theme of Site Management is also explored. Including, monitoring site environment, operation of site equipment, site security management and construction quality management. (Siddiqui, 2014) introduced an innovative sensor distribution scheme and management strategy for construction sites. Additionally, Riaz et al. (2015) delved into the core concept of the Confined Space Monitoring System, aiming to facilitate real-time safety management in the construction sector. The system's primary objective is mitigating the detrimental impacts of hazardous environmental conditions. Furthermore, this integration is used also for planning and design, for instance, Mijic et al. (2017) undertook a case study involving the city center of Banja Luka.

Finally, the integration of BIM-Sensors is also used for positioning and tracing which is very important in construction products traceability. The predominant sensor tool employed for tracking and positioning is Radio Frequency Identification (RFID) which is mentioned in the previous section. In contrast to this, Liu et al. (2018) stated that rather than using RFID technology, Bluetooth Low Energy is used in positioning and tracing. The study conducted by Park et al. (2017) employed Bluetooth Low Energy technology for object localization. This effort led to the creation of a self-correcting, knowledge-based hybrid tracking system. This system harnesses BLE beacons to ascertain absolute positioning, while motion sensors determine relative positioning. The integration of BIM provides geometric details of the building, enhancing the tracking system's reliability. The findings underscore the hybrid system's efficacy, reducing the positioning error rate by an impressive 42%.

2.10.3 BIM and Blockchain

In the ever-evolving realm of construction technology, the seamless integration of BIM and Blockchain has emerged as a transformative force, revolutionizing the way projects are conceptualized, executed, and managed. Through the development of new applications and procedures, the integration of Blockchain with other technologies such as BIM, AI, and IoT can drastically alter the mode of operation within the industry and help bring about the necessary systemic change (Shooshtarian et al., 2022). Architects, engineers, and construction experts may all collaborate on a single, shared model using BIM, which is quickly becoming a standard platform. By integrating with blockchain, it is possible to address certain shortcomings in the BIM work process (Yang et al., 2020). Data distribution across many versions of the BIM model, which results in fragmented and inconsistent management of model use and unclear ownership of a BIM model, is one of the primary barriers in implementing BIM-based systems (Turk & Klinc, 2017; Ye et al., 2018). By using smart contracts, the BIM model may only be used by parties who have authorization from those contracts, and all transactions are recorded on blockchains. Information is merged on blockchain as a result, and responsibilities and intellectual property rights are efficiently transferred (Belle, 2018). Additionally, they brought forth the cup of water theory, in which blockchain is the cup wall that redefines the storage system, IoT is the water in the cup that represents the entity of objects and data, and BIM is the bottom of the cup that manages digital information (Yang et al., 2020). Whereas, according to Lokshina et al. (2019), BIM, IoT, and blockchain are complementary technologies that enable the secure management and storage of building construction data.

Furthermore, Liu et al. (2019) stated that the integration of BIM & BC application for sustainable building design and construction process focuses on smart energy and construction management, with little attention paid to addressing challenges for applying BIM to sustainable building design and proposing strategies for sustainability goals. This is crucial for the integration of blockchain and design as it necessitates considering the role of users who are core players of smart blockchain technology for building construction project management.

A study by Yang et al. (2020) found that the field of integrating blockchain and BIM is still in its early stages, with the first publication occurring in 2017. This shows that there is still an emerging demand for this integration as it is still in its early stage to enhance the security and reliability of information exchange in a BIM workflow (Erri Pradeep et al., 2019).

Elghaish et al. (2023) proposed a Construction Circular Supply Chain (CCSChain)-based blockchain technology that offers an integrated solution to overcome barriers in adopting a circular supply chain in construction. It allows designers to incorporate existing elements in new projects by creating BIM families for reuse. Local agencies can track material details and treatment processes securely. CCSChain uniquely integrates BIM and blockchain, creating a 'bank of BIM families' for reusable items in specific areas. It enables sharing reusable BIM families for closed circular supply chain loops. Importantly, it facilitates early decision-making for maintenance and deconstruction, encouraging sustainable practices. Whereas the gap in this integrated approach is that the full automation of the solution remains to be achieved in the future. This can be achieved by integrating IoT to the proposed system. In addition, this research defined some roles of stakeholders in this implementation (e.g., asset owners, designers, operators) but did not define the role of suppliers, contractors, facility managers, waste managers/recycling companies. Furthermore, Liu et al. (2019) proposed a sustainable building design information management framework based on BIM and BC. This framework aids project stakeholders in information management, offering the capability to attain and guarantee the implementation of sustainable design goals. This is made possible through the interactive implementation of smart contracts within the user-driven BIM+ blockchain system. This system also facilitates the recording of value exchanges across three user-driven levels: namely user, system, and transaction, which defines the roles of client, architect, building structural designer, building service designer and others.

However, the research gap in this framework is the absence of real time data collection tool such as IoT, Sensors, RFID, QR etc, in addition to the role of other stakeholders that facilitate the implementation of construction CE. Furthermore, Celik et al. (2023 contributed to research by showing that the usage of blockchain in construction is lacking, and current initiatives are still in the research and development stage, and some restrictions and roadblocks have been found. Whereas, her important contribution was the proposal of a blockchain and BIM integration model, which has the potential to improve construction collaboration by eliminating third parties and preventing delays while assuring that transactions are highly secure, transparent, and traceable. Further research of this study, as suggested by the author, extends the Computational Urban Sustainability Platform created by Rezgui et al. (2021) to incorporate blockchain-related services to support stakeholders' transactions throughout the project and building lifecycle, taking the concepts of Material Passport and recyclability into consideration.

2.10.4 Blockchain and IoT

The integration of blockchain and IoT has been a topic of discussion since 2016 across various domains. The objective is to gather real-time data through IoT devices and facilitate the secure and private sharing of this data using a blockchain framework, ensuring robust privacy, security, and scalability measures (Elghaish et al., 2021). Lu (2017) stated that blockchain holds the capability to bring about innovation and substantial enhancements to IoT-related systems by establishing a distributed system. This was supported by Lu (2019) who stated that blockchain technology presents a promising avenue for addressing specific challenges within the realm of business process management (BPM). Within this context, the integration of blockchain with components of BPM systems, which commonly encompass IoT devices, emerges as a requisite measure. Different authors have studied the technological potential and challenges of this integration.

Elghaish et al. (2021) studied the research trends and opportunities of integrating IoT and blockchain in the construction industry, by proposing a new concept called blockchain of things (BCoT) to exploit the advantages of IoT and blockchain. It has been found that most of the studies that have been done for integrating IoT and blockchain are for evaluating and discussing the potential of this integration. For instance, Reyna et al. (2018) in his manual literature review study evaluated the capabilities of BC to enhance the performance of employing IoT technology. Moreover, Lo et al. (2019) discussed the technical characteristics of integrating IoT & BC, as well as the existing barriers. Furthermore, Venkatesh et al. (2020) explored the utilization of this integration to move towards Industry 4.0. Different industries were covered in this study, excluding the construction industry, same as Mistry et al. (2020) who presented a comprehensive review on blockchain based 5G-enabled IoT where the potential utilisations in the built environment sector were not critically and sufficiently analyzed.

2.11 Summary

The critical review of the extant literature has identified a research gap concerning the integration of Industry 4.0 technologies to support construction waste management. Specifically, this gap revolves around the absence of a comprehensive DIMS that encompasses the entire project lifecycle, extending from inception to demolition or deconstruction phases. In addition, most of the systems lack the support of material flow analysis. Furthermore, there is a notable lack of clarity regarding the roles and engagement of various stakeholders within these systems. Most of the information management systems reviewed in the existing literature, while promising in their potential, have exhibited shortcomings. One significant limitation is the absence of a secure and robust database infrastructure for effectively handling the vast datasets inherent in the integration of technologies like BIM and IoT or absence of real time data collection in BIM and blockchain integration. Moreover, many systems have faltered in achieving real-time data collection, a critical feature to ensure the timely and accurate tracking of waste and materials in construction and demolition processes, which will help analysing the material flow. Addressing this gap entails the development of a holistic digital platform that not only tracks and manages waste throughout the lifespan of a project, but also defines the roles and responsibilities of each stakeholder involved in the management of these systems, while incorporating material flow analysis capabilities to facilitate decision making regarding reduction, reuse, and recycling. Therefore, creating a DIMS, that integrates BIM, blockchain and IoT to facilitate decision making for circular economy principles, is essential to address the research gap. Such a system can offer secure data management, real time data collection for quantifying waste, reused and recycled products providing a comprehensive solution to enhance construction waste management, promote sustainability and resource efficiency in the construction industry.

3 Proposed Methodology

To achieve the aim of the research, DSR has been adopted as the proposed methodology for the development of the DIMS. DSR within the field of information systems represents a research paradigm focused on developing and evaluating innovative IT artefacts designed to address practical, real-world issues. The foundational principle is that knowledge and comprehension of a problem domain and its solution are acquired through the construction and application of the designed artefact (Vaishnavi & William Jr Kuechler, 2015). The general DSR methodology followed in this research is the one proposed by Vaishnavi & William Jr Kuechler (2015) (Figure 4).

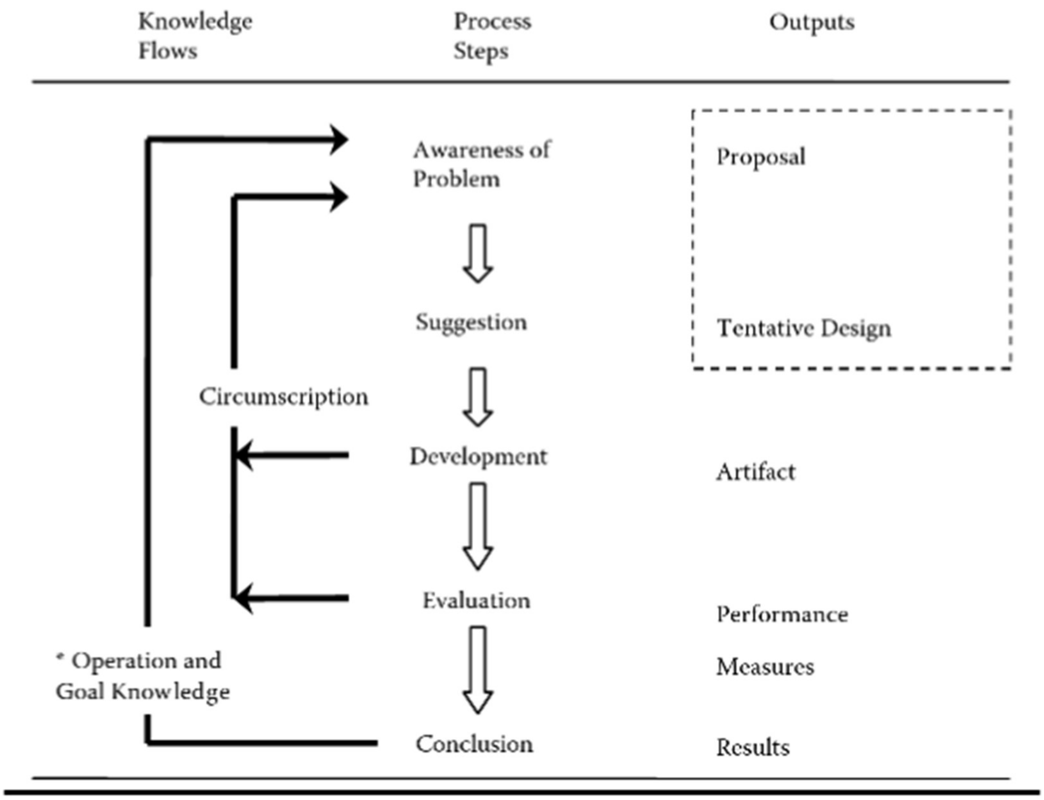

Figure 4 The general methodology of Design Science Research (Vaishnavi & William Jr Kuechler, 2015)

In the process of DSR (Figure 5), it all begins with recognising and understanding the problem. This initial step involves acquiring a comprehensive understanding of existing knowledge and prior research related to issues concerning CDW, Construction CE, barriers and drivers of CE and understanding the roles and engagements of stakeholders within CDWM. This understanding has been cultivated through the critical review of extant literature in the field, as presented in this report. This has included a simultaneous examination of Industry 4.0 technologies and their potential integration as information management systems for CDWM. Following awareness and understanding of the problem, a conceptual DIMS is proposed as a tentative design, founded on insights garnered from the literature review. Having comprehended the problems through the critical review of the literature and proposed a solution, an exploratory research phase is proposed to further investigate these problems in the industry and provide further validation to the established understanding of the current problem and check the applicability of the proposed solution. This exploration involves conducting a preliminary study targeting the construction industry, encompassing both internal experts within the RECONMATIC project and external industry experts/professionals. A questionnaire survey will be utilised to facilitate gathering valuable insights and perspectives from key team members and collaborators, and achieve objectives 1, 2 3 and partially 4. This marks the conclusion of the deductive phase of the research, which began with a general idea concerning CDWM and the integration of Industry 4.0 technologies, leading to the formulation of a proposed conceptual framework based on these concepts and their associated relationships.

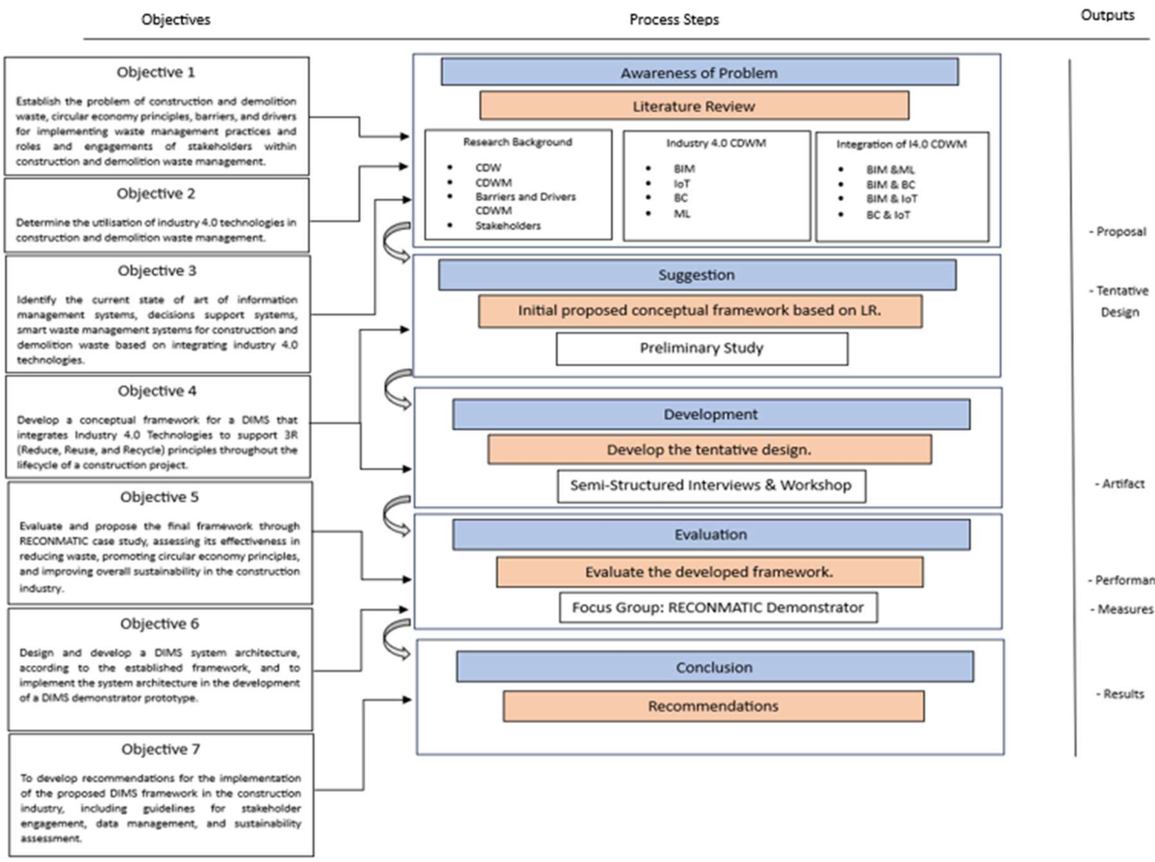

Figure 5 Design Science Research Process Flow

Following confirmation on the applicability of the proposed conceptual framework, the development of the artifact commences, embracing an inductive approach. This phase features iterative development through semi-structured interviews with internal professional partners within RECONMATIC and external experts within the construction industry. Achievement of objective 4 is the primary goal at this step of the DSR process, i.e. developing the DIMS conceptual framework that integrates Industry 4.0 Technologies to support MFA throughout the lifecycle of construction project.

Subsequently, the next step in the DSR process is to, first of all, evaluate and develop the final DIMS conceptual framework objective 5. To achieve Objective 5, the framework will be evaluated and revised to evolve the final version through focus group based on case studies from the RECONMATIC project demonstrators. Secondly, is to achieve objective 6, the developed and evaluated DIMS will be converted from its concept to its system architecture which will be implemented in the development of DIMS demonstrator prototype. Following the implementation of the prototype, the framework's strengths and weaknesses are assessed, culminating in the presentation of conclusions and recommendations to meet the research's ultimate objective, which is objective 7.

4 Progress To-date

To-date, Objectives 1-3 and partially 4 have been successfully achieved, which has led to the development of a proposed initial conceptual framework for the DIMS, which is designed to facilitate CE practices in construction (Figure 6). This high-level framework integrates BIM, IoT, and blockchain to strategically manage information across all stages of the lifecycle of a built asset project to support material flow analysis. The primary focus is on facilitating material flow analysis through tracking the products/materials and waste. Through the integration of these technologies, the framework aims to enhance building information management, enabling a more comprehensive and streamlined approach to handling crucial data throughout the project's lifecycle. Additionally, real-time data collection capabilities provided by IoT devices integrated with BIM contribute to a dynamic and continuously updated information repository. Furthermore, the incorporation of blockchain technology ensures the security and transparency of data, fostering effective stakeholder collaboration and understanding of their role and engagement in the pursuit of sustainable and circular construction practices.

The framework utilises analysis tools to inform decision-making throughout the lifecycle of a built asset project. The design phase marks the inception of a construction project and holds significant influence over its trajectory. Within this phase, two crucial elements are introduced: BIM and blockchain technology. BIM enables the creation of a detailed digital model of the project, extracting material-related information such as specifications, types, and quantities (Lin et al., 2018; Shick Alshabab et al., 2017; Cheng & Ma, 2013). This digital model serves as the foundation for generating MPs, essential for efficient material tracking and management (Atta et al., 2021). Moreover, BIM facilitates waste prediction, aiding in waste management strategies (Quiñones et al., 2022; Guerra et al., 2019; Wong & Fan, 2013).

Blockchain technology complements BIM by securely recording data such as material specifications and waste predictions (Xu & Wang, 2023; WANG et al., 2017). This decentralized platform revolutionizes traditional methods of material tracking and waste management, offering stakeholders-controlled access and secure peer-to-peer collaboration.

Transitioning to the construction phase, Radio Frequency Identification (RFID) technology is employed for real-time tracking of materials and products (Yu et al., 2022; Ren & Li, 2018;

Ruan & Hu, 2011). RFID tags affixed to items enable their scanning and recording upon arrival at the construction site, updating the blockchain and BIM databases. IoT smart Bins complement RFID technology by monitoring waste generation, facilitating MFA and waste prediction comparisons (RTS, 2023).

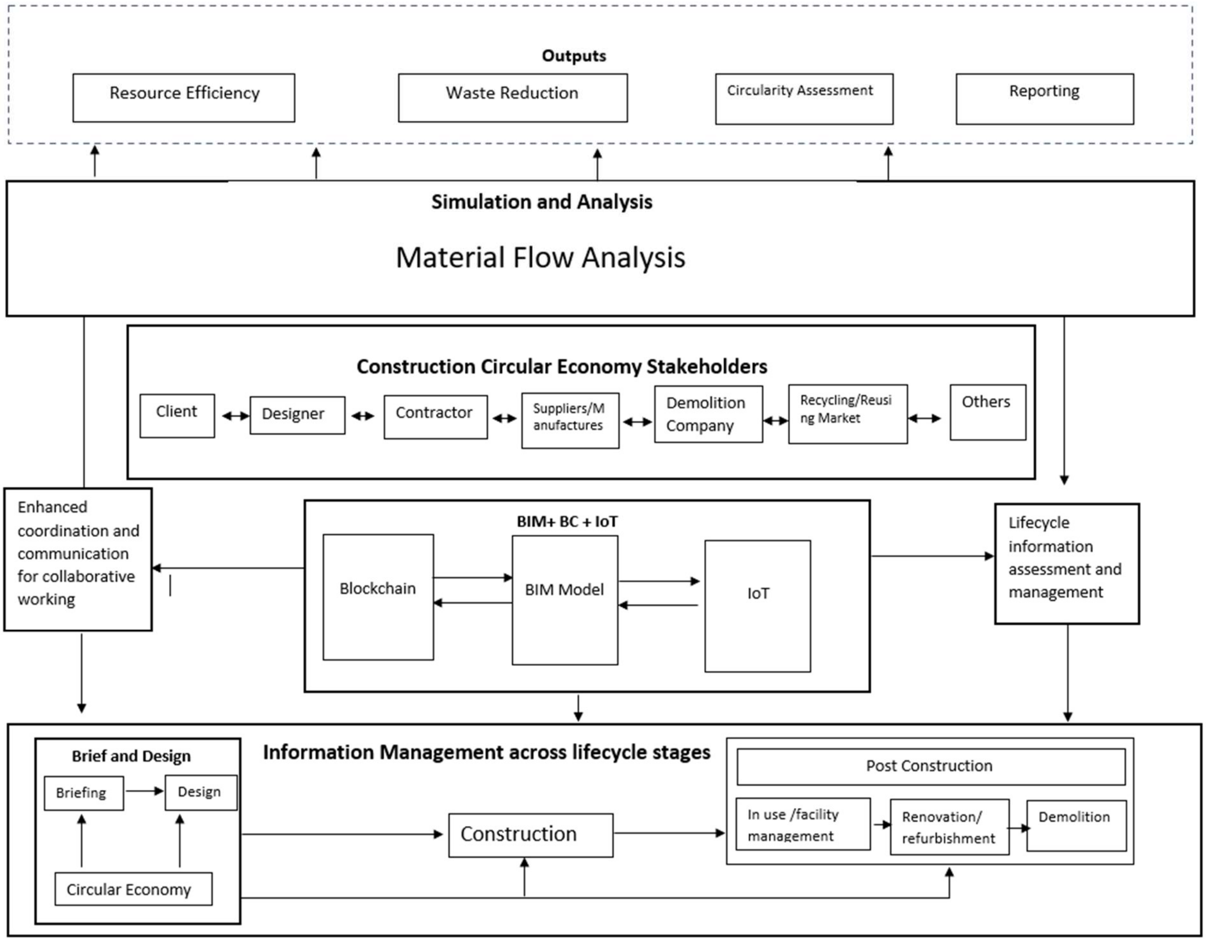

Figure 6 Initial High-level conceptual framework for DIMS

Throughout the operation phase, RFID technology continues to track material movement and utilization, with updates reflected in both BIM and BC platforms. Smart Bins persist in monitoring waste generation, supporting decisions regarding reuse and recycling for sustainability and environmentally responsible practices. At the operation phase's conclusion, the updated BIM and BC aid in planning the sustainable demolition of the building.

Finally, in the demolition phase, access to the latest BIM and BC platforms assists the demolition organization in tracing all materials and products within the structure. A deconstruction design is implemented, and waste generation during demolition is accurately predicted with insights from IoT smart Bins. The updated BIM and BC platforms facilitate decisions on material and product reuse, ensuring a comprehensive and sustainable approach to CDWM throughout the project lifecycle.

5 Conclusions

The primary focus of this research is the development of a comprehensive conceptual framework for a DIMS that seamlessly integrates Industry 4.0 technologies to support material flow analysis throughout the lifecycle. In addition to its implementation through the development of DIMS demonstrator prototype. The overarching goal is to revolutionise the management of construction and demolition waste by offering a holistic solution that covers the entire project lifecycle and incorporates material flow analysis. This research addresses a critical need in the construction industry, bridging the gap between waste management and cutting-edge digital technologies. Furthermore, it delves into the integration of Industry 4.0 principles to facilitate the tracking of construction materials and construction waste, a topic of paramount importance in the industry's ongoing digital transformation. Furthermore, by exploring how stakeholders can effectively collaborate to enhance the implementation of digital information management systems for tracking construction materials, this research delves into the organizational and human aspects of technology adoption. The comprehensive critical review and gap analysis undertaken offer valuable insights into the current knowledge landscape in the field of digital technologies in construction waste management. Moreover, the development of a practical conceptual framework for DIMS provides a structured approach for industry professionals, streamlining material flow analysis, waste reduction, and sustainability practices. The empirical validation through a real-world case study from the RECONMATIC project demonstrators sets this research apart, providing practical insights into the potential impact and feasibility of the DIMS. Ultimately, the culmination of this work in the form of recommendations and guidelines for DIMS implementation promises to offer actionable steps for stakeholders, from data management strategies to stakeholder engagement and resource efficiency. Currently, the research is at a point where it is proposing a solution to incorporate Industry 4.0 technologies such as BIM, IoT, and blockchain. This stage lays the groundwork for the subsequent phases of development, evaluation, and ultimately, the implementation of an innovative solution in the construction industry. The progress to-date positions the study to move forward into designing and develop the initial system architecture, through the implementation of the proposed DIMS framework.

This research not only makes immediate contributions, but also builds a foundation for future research to start from and add to, ensuring ongoing progress in the field. In addition, this research, while making a significant academic contribution, has the potential to create a tangible and positive practical impact on the construction sector and, by extension, the global environment.

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