13th International Conference PROCEEDINGS

25 September – 27 September 2025

Kerpic'25

"EARTHEN ARCHITECTURAL HERITAGE"

Ecole Nationale d'Architecture de Rabat / MOROCCO

13th International Conference Proceedings

Kerpic'25

"Earthen Architectural Heritage"

25 September – 27 September 2025

Organized by

Ecole Nationale d'Architecture, Rabat, Morocco & Kerpic Akademi & Kerpic Network

www.kerpic.org/2025

Edited by

Aysel TARIM, Bilge ISIK, and Khalid EL HARROUNI

Graphic-Design

Aysel TARIM

Printing Office

Ecole Nationale d'Architecture
Rabat / Morocco

ISBN

978-9920-9058-3-1

Digital Technologies in Construction Material Waste Management



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ABSTRACT

The construction industry, while providing numerous positive contributions to human life, also has negative environmental impacts, including energy and resource consumption, waste generation, and carbon emissions. In the construction industry, natural resources such as sand, gravel, stone, clay, and wood are heavily utilized, while significant amounts of water are also consumed during material production, construction site activities, and building operations. Furthermore, a substantial amount of waste is generated, particularly during the construction and demolition processes of a building's life cycle. Improper management of waste materials such as concrete, steel, wood, bricks, and paint, which can either be eliminated or minimized, poses a significant threat to environmental sustainability. Therefore, waste management, which is at the core of the circular economy, has increasingly become a critical focal point for the construction industry.

A range of strategies and practices are being developed and implemented in the construction industry to prevent, reduce, and reuse material waste throughout the building life cycle, aiming to keep construction materials within circular processes. Moreover, these strategies and practices are increasingly supported by digital technologies. Digital technologies provide several benefits, such as monitoring waste generation processes, innovatively restructuring the material supply chain, accurately calculating and planning material needs, and categorizing materials in terms of waste suitability. Furthermore, digital technologies offer significant contributions by improving waste management through the simulation of construction and demolition processes, creating a virtual replica of the real world, and enhancing the optimization and coordination of processes by integrating project data and management procedures into digital platforms.

The aim of this study is to explore how digital technologies can be integrated into construction material waste management to minimize/eliminate it. To achieve this objective, a qualitative method known as content analysis was employed to examine studies from current literature. Key digital technology themes were identified, and the existing studies were evaluated. This study is believed to be significant in revealing the current state of digital technologies in construction material waste management, which plays a crucial role in the construction industry, and in identifying the potential needs of the industry in this regard.

Keywords: construction materials, digital technologies, digital waste management, material waste management, waste management.

1 INTRODUCTION

Due to the nature of the construction industry, a wide variety and large quantities of building materials are used. This situation also brings with it the problem of the construction industry generating the highest level of waste compared to other industries [1]. In the construction industry, where a high amount of waste is generated, it has become essential to manage waste through methods such as predicting waste from the earliest process of a building life cycle, reducing waste, developing and implementing new techniques and methods for waste minimization and recycling materials. In recent years, the gradual depletion of resources and the shift from linear economic model to a circular economy model have made it necessary to focus on waste management strategies [2].

Effectively identifying, generating solutions and managing the evolving and growing needs of people through data-driven approaches is important not only for ensuring a human-centered perspective but also for contributing environmental and economic sustainability. According to Top Bim Company's evaluation [3], in the construction industry as well, it is crucial for professionals to follow emerging technologies and design innovations, as this plays a critical role in the construction industry's development. This knowledge base is effective in anticipating changes in today's world and developing appropriate strategies. In this way, the industry will not only be able to adapt to evolving needs but also deliver long-term value through meaningful work. This process also makes a significant contribution to the overall advancement of the industry. Furthermore, this company mentions that construction technology trends watch in 2023-2030 will be focused ten technologies: sustainability and green building, Building Information Modelling (BIM), modular and prefabricated construction, virtual and augmented reality, robotics, 3D printing, autonomous construction equipment, Internet of Things (IoT), Artificial Intelligence (AI) and Big Data and Analytics [3]. However, despite the potential of digital technologies to support sustainability strategies, their implementation in construction waste management is still limited and challenged by various obstacles [4].

To reduce the negative environmental impacts of the construction industry, it is necessary to implement and monitor waste management practices throughout the building life cycle processes. In doing so, understanding the potential implementation areas of emerging and increasingly widespread digital technologies in the construction industry is essential for effectively integrating these technologies into the industry. Therefore, this study aims to investigate potential digital technologies applicable to construction waste management throughout the building life cycle from a holistic perspective. To achieve this, a content analysis method was employed to examine relevant studies from the current literature. Key digital technology themes were identified, and evaluated in relation to the main processes of the building life cycle: pre-construction, construction, and post-construction.

2 CONSTRUCTION WASTE MANAGEMENT AND DIGITAL TECHNOLOGIES

It is widely recognized that the construction industry generates a significant amount of material waste, which is classified as a type of physical waste. Construction and Demolition Waste (CDW) represents the largest share of total solid waste in many European Union countries [1]. Furthermore, according to the waste and recyling statistics 215 million tons of total waste were generated in the United Kingdom in 2024, of which 62% of belonged to CDW [5]. Also, in United States (US), EPA's [6] report shows that in 2018, 600 million tons of CDW debris were generated. According to the report, in the United States, concrete from CDW constituted the largest portion at 67.5%, followed by asphalt concrete at 17.8%. Wood products made up 6.8% of CDW, while all other materials combined accounted for the remaining 7.9% [6]. The same report shows that demolition waste has a greater impact compared to construction waste, whereas approximately 457 million tons were directed to next use, and over 143 million tons of CDW debris were sent to

landfills in 2018. The subsequent uses of these materials are evaluated as compost and mulch, manufactured products, fuel, soil amendment, and, in addition to these methods, aggregates and others as the most preffered usages, among others.

CDW has a crucial role for waste generation. Although recycling of waste generated during construction and demolition processes is possible, this represents only one step in waste management. Throughout the building life cycle, including the internal cycles of material production, strategies for waste prevention should be developed starting from the during pre-construction processes, including design process, and appropriate measures must be taken alongside proper planning. For successful waste management, the building life cycle, which includes the pre-construction, construction, and post-construction processes, could be evaluated from a circular economy perspective in accordance with the 10R strategies. These strategies focus smarter product use and manufacture (refuse, rethink and reduce), extend lifespan of product and its parts (reuse, repair, refurbish, remanufacture and repurpose) and useful applications of materials (recycle and recover) [7]. To apply these strategies within the framework of construction waste management, today's advanced technologies should be considered to enhance the effectiveness of the management process. A data-driven and well-structured waste management system must be developed through the integration of digital technologies. To illustrate, Zhao et al. [4] have put forward the idea that effective information management plays a critical role in construction waste management. In this context, material passports are increasingly recognized as a promising tool to enhance traceability and support circular resource strategies. They have also asserted that the implementation of material passports should be based on the integration of various technologies, including BIM, blockchain, and Radio Frequency Identification (RFID).

3 CONTENT ANALYSIS AND DISCUSSION

Digital technologies play a preventive, monitoring and optimization role in whole processes in the building life cycle. While foresight and design optimization are at the forefront in the pre-construction process, material management and process monitoring play an active role in the construction process, and technologies for recovery and documentation play an active role in the post-construction process [32]. Also, IoT technologies can be used to support waste management throughout all processes of the building life cycle. However, it is noted that the use of technologies such as robotic systems and waste management sensors remains low, pointing to limitations such as technology awareness, budget constraints and lack of training [8].

Table 1. Building project lice cycle processes and digital technologies.

Building Project Life Cycle Processes	*Digital Technologies*
Pre-construction Process	AI, Blockchain Technology, BIM, Digital Twin, IoT, Machine Learning, Material Passports (MPs), Mobile Applications and Smart Platforms
Construction Process	
Post-construction Process	

To have a general understanding of digital technologies integration into construction management throughout building life cycle, a content analysis was employed. Content analysis is defined as a data analysis method that adopts a systematic approach to examine textual, visual, or verbal communication data. Quantifying words, concepts, themes, phrases, characters, or sentences within a dataset helps draw meaningful conclusions from the information [9]. Therefore, this study reviewed the prominent digital technologies in the current literature, focusing on their intended applications in relation to the main stages of the building life cycle (Table 1).

3.1 Pre-construction Process

Pre-construction process is one of the most important processes for building life cycle because of designing and planning whole processes. In construction waste management, the aim during the pre-construction process is to reduce waste generation before it even begins, to predict material flows and to increase the potential for reuse and recycling [10]. In the pre-construction process, the prominent digital technologies and their intended uses for construction waste management are presented in Table 2.

Table 2. Pre-construction processes and digital technologies.

Digital Technologies	***Purpose***
Artificial Intelligence (AI)	-estimation of the amount of waste based on previous projects [4], [11]
Blockchain Technology	-enhancement of the traceability of the material source [4], [10] -waste information management [12]
Building Information Modelling (BIM)	-waste reduction [13], [14], [4], [15], [10], [16] -visual demolition waste management planning [17] -waste reuse [17] -waste recycle [17] -waste prevention [14] -provision of the basic data infrastructure for creating a material passport [4] -implementation of material logistics and inventory tracking, resulting in reduced losses [15] -waste information management [12], [11] -simulation of the demolition process for demolition waste management [18] -waste calculation for building demolition [19]
Digital Twin	-prediction of waste generation [20] -waste estimation [20] -waste quantitative assessment [18] -demolition process planning [18] -optimal disposal route selection [18] -waste management strategy [18]
Internet of Things (IoT)	-real-time monitoring of waste generation and tracking of components enabled by Radio Frequency Identification and sensors [15], [8] -support for blockchain technology in waste information management [12] -provision of data for resource utilization and logistics strategies [11]
Machine Learning	- optimization of materials incorporating waste-derived components [21], [22] -prediction of waste generation [23]
Material Passports (MPs)	-guidance of design decisions based on the reusability and recyclability of building components throughout their life cycle [24], [15] -provision of sustainable material criteria such as product content, toxicity, durability, and reuse potential [24], [15] -contribution to data standardization from product level to building level [15] -providing information for future dismantling processes [25]
Mobile Applications	-
Smart Platforms	-ensuring transparent information flow between all actors through electronic tendering, browser tagging, and online communication tools

	(e.g., email, social media), contributing to the prevention of erroneous decisions and resource waste [8]

According to Table 2, BIM, digital twin and MPs are the preferred and range usage area for pre-construction processes. On the other hand, for waste data information blockchain technology, IoT and smart platforms are preferred whereas mobile applications are not preferred. Also, digital technologies are commonly used for waste prediction, waste estimation and construction and demolition processes planning.

Digital technologies play a role in making decisions that prevent waste generation in the pre-construction process. With BIM, the amount of waste can be predicted at the design process and material selection can be optimized. AI develops waste prediction models by learning from past projects. Blockchain enables secure and transparent management of material passports [4]. MPs enable designers to make decisions based on criteria such as material selection, modularity of building components and disassembly potential. By creating a transparent information infrastructure in the preconstruction process, it enables the reuse of products and systems [24]. Blockchain ensures that material and component information is recorded in a transparent, verifiable and traceable manner during the pre-construction process [10]. In a study addressing the waste management of plastic-based materials, BIM was proposed as a tool to analyze potential waste generation during the construction process in advance, enabling more efficient planning. MP were recommended to provide essential information on the identity, durability, and reusability of the materials used. Additionally, AI-supported decision-making systems were suggested for developing scenarios that minimize waste generation by considering parameters such as material selection, modularity, and design flexibility [26]. Also, IoT plays a significant role in pre-construction processes for planning, resource allocation and material tracking [8].

Digital technologies can be applied to various types of materials, such as earthen materials, recycled materials, or new materials in the pre-construction process. Similarly, these technologies can be utilized for different types of buildings, including new constructions and heritage buildings. For example, BIM helps create 3D models of each type of structure, which can be used for material quantity calculations and structural analyses aimed at waste reduction and waste information management. Additionally, AI and machine learning assist in analyzing structures and determining the best design options for waste management by transferring historical and environmental data. Furthermore, digitally recording the properties and origin of each material used aids in tracking material waste across all types of construction and monitoring how, where, and in what manner these materials are reused or processed.

3.2 Construction Process

Construction process is a key process which has high material usage and produces waste because of implementation. Table 3 presents the key digital technologies and their intended applications for construction waste management during the construction process.

Table 3. Construction processes and digital technologies.

Digital Technologies	***Purpose***
Artificial Intelligence (AI)	-high-accuracy automatic classification of waste enabled by the combined use with image analysis [4] -prompt-guided waste segmentation [27], [28] - data collection on material usage [29]
Blockchain Technology	-ensuring transparency by recording information about when and where materials were used or converted into waste on the blockchain [10] -waste information management [12] - tracking recyclable waste [10], [11]

	- monitoring logistics processes [10] - secure data sharing between authorized users [10] - use of smart contracts for transparency and accountability [11]
Building Information Modelling (BIM)	-waste reduction [14], [11] -waste reuse [17] -waste recycle [17]
Digital Twin	-waste quantitative assessment [18] -demolition process planning [18] -optimal disposal route selection [18] -waste management strategy [18]
Internet of Things (IoT)	-real-time monitoring of material utilization and waste generation at the construction site [4], [16], [11] -support for blockchain technology in waste information management [12] -data collection on material usage [29], [11]
Machine Learning	-prediction of waste generation [20] -vision language model for waste classification [30] -material waste sorting [31] -waste estimation [32]
Material Passports (MPs)	-identification of each individual material and component on site thanks to material passports, reducing over-ordering and waste [24], [15] -provision of information on proper storage of materials arriving on site and prevention of material loss [24], [15]
Mobile Applications	-categorization of waste generated in the field and initiation of the recycling process through mobile applications [26], [16] -on-site data entry [33] -waste tracking [33] -waste reporting [33]
Smart Platforms	-ensuring worker safety during the construction process with smart watches and health sensors, minimizing work accidents and damage requiring reconstruction [8]

According to Table 3, AI, blockchain technology, machine learning and mobile applications have high usage area in the construction process. are the most preferred and range usage area for pre-construction process. Mobile applications are generally preferred for waste tracking, waste reporting and blockchain technology is generally used for waste information management whereas AI and machine learning are preferred for waste prediction and waste sorting.

During the construction process, IoT sensors instantly monitor material mobility and waste generation. Computer vision and deep learning are used for automatic identification and classification of waste. BIM is used in material tracking, inventory management and integration [4]. MPs provide transparency in the supply chain, contributing to waste reduction and proper resource utilization [24]. Blockchain records material movements, waste generation and on-site processes during the construction process and ensures secure data sharing [10]. Also, within the context of managing plastic-related waste, QR code systems, mobile applications, and IoT-based sensors are proposed during construction process [26]. During the construction process, IoT-based applications reduce waste generation by enabling real-time monitoring and improving occupational health and safety [8].

In the construction process, generally digital technologies help to follow any type of building's material flow for waste management processes and steps like waste tracking, waste reporting, on-site data entry, reduction, reuse, recycling. To illustrate, when digital twin creates a copy of building, it gives an opportunity to follow all materials in terms of waste, too. Also, IoT makes real-time monitoring of material utilization and waste generation at the construction site. This can be important, especially for heritage sites to follow original materials and reuse. Mobile

applications can support this system to create a general communication network for historical materials and preservation.

3.3 Post-construction Process

Due to activities such as demolition and site clearance, the post-construction process results in substantial material waste. To ensure effective waste management, the prominent digital technologies associated with this process are listed in Table 4.

Table 4. Post-construction processes and digital technologies.

Digital Technologies	***Purpose***
Artificial Intelligence (AI)	-use of demolition data to estimate waste quantities and recovery potential [15] -prompt-guided waste segmentation [27], [28]
Blockchain Technology	-securing material mobility by creating transparent records in the waste disposal process [4], [10], [11] -material tracking and secure data sharing [15], [10], [11] -waste information management [12], [11]
Building Information Modelling (BIM)	-visual demolition waste management planning [17], [11] -waste reuse [17] -waste recycle [17] -calculation of the amount of waste, carbon emissions, and recyclable ratios occurring after building demolition with Life Cycle Assessment (LCA) integration [4] - waste quantity assessment, optimal disposal routes and waste management strategy selection [18]
Digital Twin	-waste quantitative assessment [18] -demolition process planning [18] -optimal disposal route selection [18] -waste management strategy [18]
Internet of Things (IoT)	-support for blockchain technology in waste information management [12] -early detection of structural damage through Structural Health Monitoring, preventing demolition or major repairs [8] -provision of data by waste management sensors for recycling, separation, and waste volume reduction [8]
Machine Learning	-contactless assessment of in situ building materials for reuse potential [34] -vision language model for waste classification [30] -material waste sorting [31] -waste estimation [32]
Material Passports (MPs)	-support for the post-demolition recovery process through providing information on material composition, reusability, and recyclability [4], [24], [16] -increase in the transferability of materials used to new projects [24], [15] -integration of material passports (MPs) into second-hand material markets through digital platforms [24], [15]
Mobile Applications	-on-site data entry [33] -waste tracking [33], -waste reporting [33]
Smart Platforms	-

As shown in Table 4, mobile applications, IoT, AI, and blockchain technology and MPs are commonly used to provide and track data for waste information management, whereas smart platforms are not utilized in the post-construction process.

BIM and LCA integration in post construction evaluates material recycling potential after demolition. MPs provide material history for reuse and recycling processes. Big data and blockchain support traceability of waste streams [4]. MPs enable selective demolition processes by providing information on where and how materials can be removed during the demolition process. It acts as a digital bridge for material banks and systems working in connection with the secondary use market [24]. Also, blockchain can be used to ensure digital accuracy for the recovery and reuse of components at the end of a building's life cycle during the post-construction process [10]. Furthermore, as part of an analysis on how to manage plastic-based materials more sustainably, blockchain-supported MPs are recommended to identify the plastic components present in the building, along with their properties and reusability potential during the demolition process [26].

In the post-construction process, digital technologies help increase the transferability of materials used to new projects. This can be a great advantage, especially for historical buildings during restoration processes. In demolition projects, these technologies can support waste tracking, waste reporting, waste information management, and even the use of vision-language models for waste classification.

4 CONCLUSION AND FUTURE STUDIES

Construction and demolition waste represents a significant share of the world's total waste and poses serious environmental risks. Consequently, effective waste management throughout the main processes of the building life cycle remains a critical challenge within the construction industry. Establishing a data-driven and well-structured waste management system utilizing digital technologies is essential. Automated and optimized strategies for construction and demolition waste management are key to advancing 10R strategies.

In the pre-construction process, digital technologies such as AI, digital twin, BIM, machine learning are preferred for waste estimation. On the other hand, blockchain technology, IoT, MPs and smart platforms are used to provide waste information management. These technologies are generally implemented for waste segmentation and waste tracking in construction and post-construction processes. Also, all these technologies provide significant contributions to waste tracking and management of all types of materials in both historical and new buildings. Using these technologies like AI, BIM, IoT, and digital twins, it becomes possible to reduce waste, monitor materials, and enable their reuse. These technologies support sustainable construction and restoration processes.

There are a wide range and effective usage areas of these digital technologies in construction waste management. However, the current approach to construction waste management remains largely conventional. Digital technologies have significant potential to transform construction and demolition waste management. Especially with the rapid development and increasing widespread use of digital technologies, their application in the construction industry is becoming essential. This is particularly important for construction waste management due to limited resources and the need to ensure environmental and economic sustainability as well as promote a circular economy. In future studies, case studies can be conducted on the application of digital technologies across different building types—such as historical and newly constructed buildings—and various material types, including earthen, recycled, and modern materials, throughout the building life cycle processes. Additionally, the barriers to better integration of these technologies into the construction industry can be identified and analyzed.

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