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Systematic Review

Barriers to Adopting Digital Technologies to Implement Circular Economy Practices in the Construction Industry: A Systematic Literature Review

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Abstract: The construction industry is a resource- and energy-intensive sector, and, thus, it has been criticised due to rising environmental concerns. As a result, it has gained heightened interest in the concept of the circular economy (CE) over the last decade due to its ability to promote the slowing, reducing, and closing production and consumption cycles of materials and products used in construction projects. Current research studies suggest that digital technologies may enhance the construction industry's ability to integrate the concept of CE into its practices. However, a clear understanding of digital technology (DT)-related barriers that hinder practical implementation of CE appears to be lacking within the sector. Thus, this study aims to identify the barriers to adopting DTs to implement CE practices in the construction industry. A systematic literature review was conducted by reviewing twenty-eight (28) relevant papers published until March 2024 in the Scopus and Web of Science databases. The VOS viewer software (version 1.6.11) was used to perform a co-occurrence analysis of keywords to identify new and popular study areas in the field. The content analysis was used to analyse the significant barriers to adapting DTs to implement CE in the construction industry; frequency and Pareto analyses were used to determine the most critical obstacles. This study identified thirty-seven (37) barriers to using DTs to implement CE, categorised into nine areas: organisational, infrastructure, regulatory, standardisation, investment, nature of the construction industry, technological, stakeholder, and data-related barriers. Of these thirty-seven barriers, nineteen were identified as critical barriers based on Pareto analysis. These findings will benefit construction practitioners and policymakers who want to adopt DTs to integrate CE practices in the construction industry.

Keywords: barriers; circular economy; construction industry; digital technologies

Citation: Thirumal, S.; Udawatta, N.; Karunasena, G.; Al-Ameri, R. Barriers to Adopting Digital Technologies to Implement Circular Economy Practices in the Construction Industry: A Systematic Literature Review. *Sustainability* **2024**, *16*, 3185. https://doi.org/10.3390/su16083185

Academic Editors: Amos Darko, David J. Edwards, Antonio Boggia and Michael Adabre

Received: 13 February 2024
Revised: 29 March 2024
Accepted: 9 April 2024
Published: 10 April 2024

1. Introduction

The construction industry practices are highly resource-intensive; they deplete vast amounts of natural resources; and they produce massive amounts of waste. They are also incredibly energy-intensive, causing significant environmental effects by raising carbon emissions [1–12]. The industry's status quo further exacerbates ecological problems and compromises the environment's capacity for sustaining future generations [8]. Thus, addressing these concerns has become imperative in the construction industry to achieve the goals related to sustainability [1,4]. Researchers have highlighted that to ensure the sustainable use of resources and energy, the linear economic model must be rethought in terms of the circular economy (CE) [4,6,13,14]. Similarly, ref. [2] highlighted the environmental and economic restrictions on the existing linear model, accelerating swift ecological and circular transformation.

The concept of the circular economy (CE) has transcended into this domain to solve construction needs amid resource constraints [4]. The concept of the CE provides an opportunity to enhance the value of resources by slowing, reducing, and closing production and consumption cycles [15]. Moreover, CE enhances resource lifespan and durability by incorporating them into the loop for as long as feasible [4]. Similarly, the fundamental objective of systemic circularity in construction entails making sure that the product system for buildings is well planned, circularly designed, and has the essential reverse cycles, system conditions, and business models to ensure the seamless reusability of building materials at the end of life [6]. Thus, various CE initiatives such as building information modelling, urban mining, secondary materials markets, deconstruction design, and construction and demolition waste (CDW) hierarchy are progressing in distinct directions [5].

The building and construction sector uses a great deal of materials that are created and operated in a linear economy [15]. The majority of pre-existing buildings and civil infrastructure adhere to the conventional cradle-to-grave paradigm and are not generally intended to be "deconstructed" or "disassembled" to eventually enable the reuse or recycling of their materials, subsystems, or components [16]. Hence, a comprehensive redesign of systems, processes, and products is required to achieve the ideal economy. Seamless integration of the cradle-to-cradle principle for a whole building's life cycle is a complex endeavour [17]. Yet, this transformation can only be accomplished with the right technology and approaches [1]. It demands innovation in the construction industry's production and consumption with their associated technologies [14].

Thus, construction companies have begun to re-evaluate their strategies, considering the volume of waste produced by the industry [4]. In contrast to conventional linear models, which involve the fabrication, building, use, and demolition of components, CE approaches have surfaced as viable substitutes by adhering to the closed-loop strategy, wherein material components undergo fabrication, building, use, disassembly, reworking, and reuse [18]. Furthermore, utilising spatial reversibility (leasing, renting, and renovating) in construction could be challenging even though they are incredibly beneficial circular strategies [4]. Thus, the construction sector faces new obstacles to boosting productivity by adhering to more sustainable, circular, and technologically sophisticated principles [19]. Furthermore, the increasing complexity of projects and project-based organisations in the construction industry concerning the number of stakeholders and establishments, technological or digital domain-specific prerequisites, supply chains and production processes, service outsourcing, and policy regulations have brought platforms (digital ecosystems) to the forefront as comprehensive solutions for cooperation and joint added value generation [20]. However, it is challenging for construction organisations and other important stakeholders to integrate strategies that ease the shift to CE [1].

Digital technologies are revolutionising the value of co-creation and collaboration beyond historical industry boundaries, with the potential to significantly impact the construction industry's ability to realise the importance of applying circular economy principles [2–4,6,9,14,16,18–24]. Advanced digital tools are being implemented across industries, owing to the boost given by the fourth industrial revolution [4]. However, integrating DTs that help transition to CE is challenging for construction companies and other vital stakeholders [1]. Switching from a linear to a circular flow for materials and components will require significant contributions from various stakeholders [16,19]. Furthermore, ref. [3] reinforced that collaboration amongst multiple stakeholders, including governments, researchers, designers, manufacturers, construction companies, recyclers, and suppliers, is necessary to build a new circular economy business model for the built environment. Significant technological developments have recently opened the chance for the construction industry to invest in state-of-the-art technologies [25]. Thus, the construction sector is undergoing a gradual yet continuous transformation to adopt novel technologies like artificial intelligence (AI), digital twins, BIM (building information modelling), material passport (MP), IoT (internet of things), digital market place (DMP), big data analytics, blockchain [3,4,9,12,14,21,24,26], radio frequency identification (RFID) [2,24], 3D printing

[4,19], cloud computing and augmented and virtual reality [4], object detection and computer vision [9] and geographic information system (GIS), and modelling and simulation [24] to commit to the built environments' circularity, efficiency, productivity, precision, and safety. As a result, to facilitate this digital transformation, enormous amounts of data are generated, and systematic data analysis and predictive modelling can be used to produce creative structural and architectural designs, increase construction speeds, improve payback periods, lower construction and operational costs, and reduce embodied and operational energy requirements [21]. In addition, the digital transformation of the construction industry has given stakeholders ample tools at every stage of the project, improving teamwork, accelerating the design and construction phases, maximising building maintenance, and ensuring appropriate end-of-life disposal [17]. However, the construction industry attempts to apply new technologies within conventional processes, so it does not fully achieve the expected economic, technical, and processual benefits that new technologies offer, even with the extensive integration of digital tools and technologies, which would require innovation in practices [20].

Thus, the idea of the CE as an alternate route to move towards a sustainable economy has drawn increasing attention from numerous governments, organisations, and scholars [26]. Some authors argue that even though the circular shift in the construction industry is complex, challenging, and highly multidisciplinary, it can be significantly aided by emerging Industry 4.0 technologies [2]. As a result, the prevailing debate in academia asserts that DTs are crucial facilitators of CE in the construction industry [26]. Information and communication technologies (ICT) are acknowledged as possible solutions to facilitate CE-oriented decision-making in the construction industry [24]. By utilising a multiple case study with three social housing organisations at the forefront of circularity implementation in the Netherlands, ref. [26] investigated how large-scale social housing organisations use DTs in their circular new build, renovation, maintenance, and demolition projects, as well as the barriers they encounter. Some authors argued that incorporating the circular economy in the built environment is expected to be achievable by DTs [26]. However, there is an apparent absence of knowledge on the practical use of DTs and their potential benefits for industry stakeholders [26]. Thus, a thorough awareness of the barriers, risks, enablers, and accelerators associated with the socioeconomic structure of the construction sector is necessary for the real-world application of CE [1,5]. In addition, institutional, behavioural, and socioeconomic changes must be made on a systemic level to realise the intended benefits [17]. Even if DTs have a promising future, several important implementation-related issues still need further research [26]. Moreover, it impeded the industry's digitalisation for CE as an emerging research area.

A robust literature review reveals that studies on DTs that enable CE in the construction industry focus more on how DTs can facilitate CE adoption. However, how different barriers hinder DT-enabled CE adoption in the construction sector remains undiscovered. Therefore, the present study addresses this research gap by identifying obstacles impeding the implementation of DT-enabled CE in the construction industry. Thus, the aim of this study is to identify the barriers to adopting DTs to implement CE practices in the construction industry. A systematic literature review was undertaken to assess the relevant papers published until 22 March 2024. Consequently, this research takes an in-depth approach incorporating content analysis, frequency analysis, and Pareto analysis to investigate the body of knowledge regarding the barriers to adopting digital technology-enabled CE in the construction sector. The rest of the paper is structured as follows: Section 2 describes the research methodology; Section 3 focuses on the research findings; Section 4 provides a detailed discussion of the research findings; and finally, Section 5 summarises the conclusions of this study.

2. Materials and Methods

This research adhered to the detailed protocol specified in the checklist provided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) which is annexed as Supplementary Materials. The criteria for choosing publications, the search plan, the metadata, the extraction process, and the data analysis steps were all outlined in the review protocol. Numerous databases, including Scopus, Web of Science, Google Scholar, and ScienceDirect, can be used to retrieve data to carry out systematic literature reviews. Scopus and Web of Science databases were selected to undertake the systematic literature review in this research. The following search query retrieved the study titles, abstracts, and keyword data.

(TITLE-ABS-KEY ("Construction") AND TITLE-ABS-KEY ("Circular Economy") AND TITLE-ABS-KEY ("Technology*" OR "Digital technology*" OR "Digitalisation" OR "Industry 4.0") AND TITLE-ABS-KEY ("Barrier*" OR "Hindrance*" OR "Constraint*" OR "Obstacle*" OR "Challenge*")) AND (LIMIT-TO (LANGUAGE, "English"))

An outline of the complete process that directed this systematic literature review is presented in Figure 1.

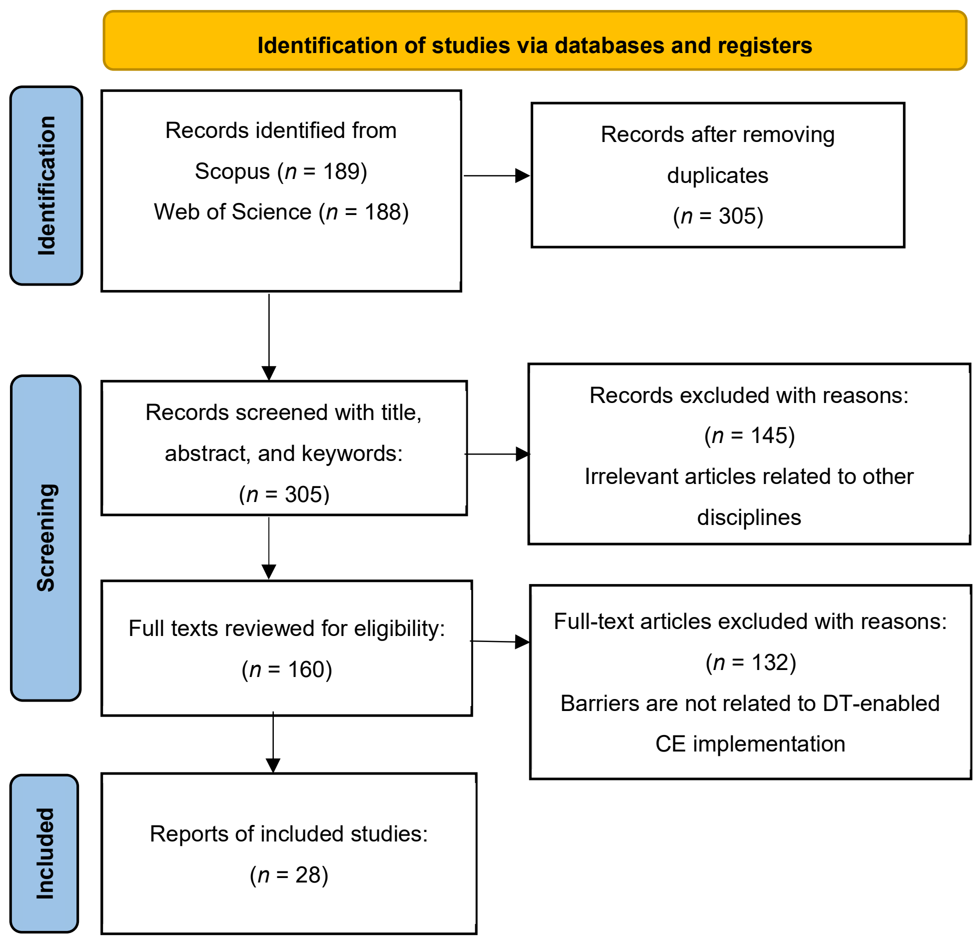


Figure 1. Flow diagram of the literature selection for review.

A total of 377 articles were screened using the initial search query, and 72 articles were excluded to avoid redundancy, as shown in Figure 1. The selection of the literature was benchmarked using the inclusion and exclusion criteria. The inclusion criteria in this research cover studies strongly connected to DT-enabled CE in the construction industry. This inclusion criterion was created to identify the barriers to CE from a substantial body of research. DTs enable the CE in the built environment to remain in its early stages. A non-English-language study was deemed to meet the exclusion criteria and was not included in the review analysis. To ensure that no relevant research was missed, the selection of literature was not limited by article types, publication years, or nations.

One hundred and forty-five (145) papers were excluded in the first screening process based on titles, abstracts, and keywords, as those were related to other disciplines. It left 160 articles, which were further shortlisted after reading the full text as the barriers were not related to DT-enabled CE implementation. Finally, 28 papers were included in the full-text review to identify barriers to DTs that enabled CE uptake in the construction industry. Table 1 provides an overview of the 28 studies selected for inclusion.

Table 1. List of the eligible studies.

No	Reference	Year	No	Reference	Year
1	Oluleye et al. [6]	2023	15	Baduge et al. [21]	2022
2	Cetin et al. [26]	2022	16	Kovacic et al. [20]	2020
3	Ababio [1]	2023	17	Nik-Bakht et al. [16]	2021
4	Harichandran et al. [3]	2023	18	Shojaei [23]	2019
5	Munaro and Tavares [5]	2023	19	Bellini and Bang [27]	2022
6	Yu et al. [24]	2022	20	Fonseca and Matos [19]	2023
7	Atta [18]	2023	21	Oluleye et al. [15]	2023
8	Geoghegan et al. [28]	2022	22	Wuni [10]	2022
9	Lavagna et al. [14]	2023	23	Osei-Tutu et al. [8]	2023
10	Giovanardi [2]	2024	24	Banihashemi et al. [17]	2024
11	Jemal et al. [4]	2023	25	Takyi-Annan et al. [25]	2023
12	Rodrigo et al. [9]	2023	26	Honic et al. [11]	2021
13	Oluleye et al. [7]	2023	27	Chi et al. [13]	2023
14	Jayarathna et al. [22]	2023	28	Jiang et al. [12]	2023

A yearly trend analysis was conducted to comprehend the field's evolutionary progress. Subsequently, these chosen articles were exported to VOS viewer (1.6.18 version) for additional processing to obtain valuable insights. The investigations of "co-authorship", "citation", "bibliographic coupling", and "co-citation" did not reveal any relationships between the selected articles. Thus, keyword co-occurrence analysis was conducted via VOS viewer software to discover the field's novel and trending research hotspots. Content analysis is utilised in this systematic review to provide novel perspectives derived from synthesising chosen studies and summarise the currently available data. Considering this, the contents of the articles were qualitatively analysed to identify barriers to adopting digital technology-enabled CE in the construction industry. A barrier category frequency analysis was undertaken to find which barrier categories frequently popped up from the chosen articles. As the secondary data set consisting of citation frequencies constrained the range of analytical methods that could be applied, a Pareto analysis was conducted to determine the most significant barriers from the obstacles that impede the implementation of digital technologies that enable circular practices in the construction industry. Pareto analysis was deemed suitable for ranking the barriers and identifying the most significant obstacles based on the studies conducted by [29,30].

3. Results

3.1. Yearly Distribution of the Retrieved Articles

The yearly trend of publications in DT-enabled CE in construction is shown in Figure 2.

As shown in Figure 2, twenty-eight (28) articles included in this study were published between January 2019 and 22 March 2024 (the publication year limitation was not included in the search query). Thus, it could be argued that scholarly attention to the barriers associated with adopting DTs to enable the implementation of CE in buildings began in 2019.

There has been a discernible rise in the attention and awareness of barriers to the uptake of DTs to implement CE in the construction industry since 2021. As the search date was limited until March 2024, the number of publications in 2024 was modest. Comparatively, many studies focused on the barriers associated with implementing DT-enabled CE in the building sector in 2023.

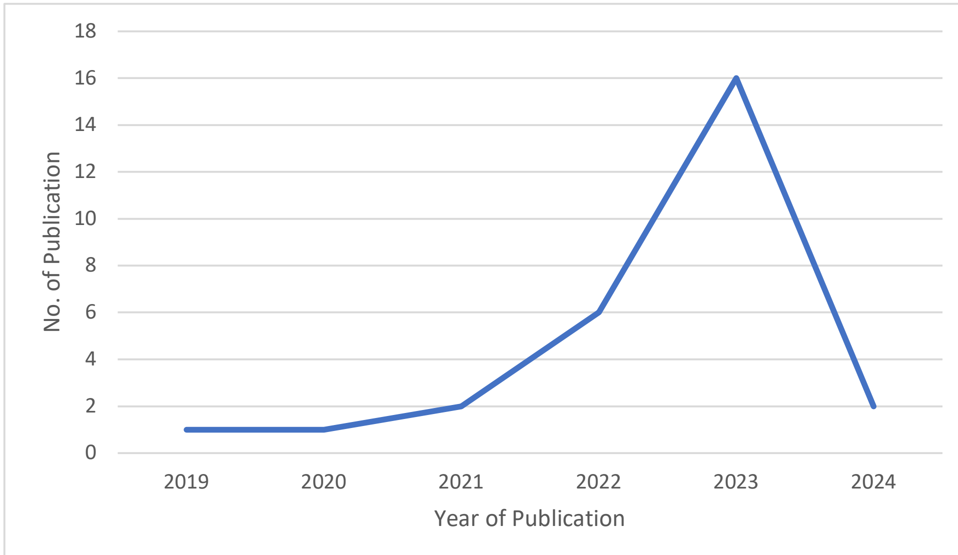


Figure 2. Trend of publications in DT-enabled CE barriers in construction.

3.2. Keyword Co-Occurrence Analysis

Keyword co-occurring analysis in databases helps researchers identify hotspots in a field and understand study themes and subtopics within a particular area. Thus, keyword co-occurrence analysis was performed on 28 articles in this study using the VOS viewer software. Additionally, a thesaurus file was made to make cleaning data easier by combining phrases that refer to similar ideas (for example, building information modelling and BIM are synonymous; thus, they were combined and presented as BIM). The result of this analysis is illustrated in Figure 3 for a minimum threshold of two keywords to include all the selected papers of this study.

The figure illustrates the frequency of co-occurring terms based on the size of nodes, the relationship between nodes based on node proximity, and the strength of connection based on the thickness of connecting lines. Nodes labelled "construction industry", "circular economy", "barriers", and "digitalization" are the most frequently appearing co-occurring keywords from the chosen research papers. Moreover, the proximity and thickness of the lines reflect their interrelated solid connection. Strong links to other keywords indicate that these keywords represent prominent study fields that have drawn significant attention.

The illustration depicts various DTs, such as "artificial intelligence", "internet of things", "building information modelling", "digital twin", "blockchain", "big data", and "material passport" as nodes that were applied to implement CE in the construction industry from the selected research articles. An additional indication that the process of incorporating digital technology into the construction business has begun is provided by the nodes designated "digitalisation", "digital technology", and "information technology". These relationships are further demonstrated in Figure 4, as shown below.

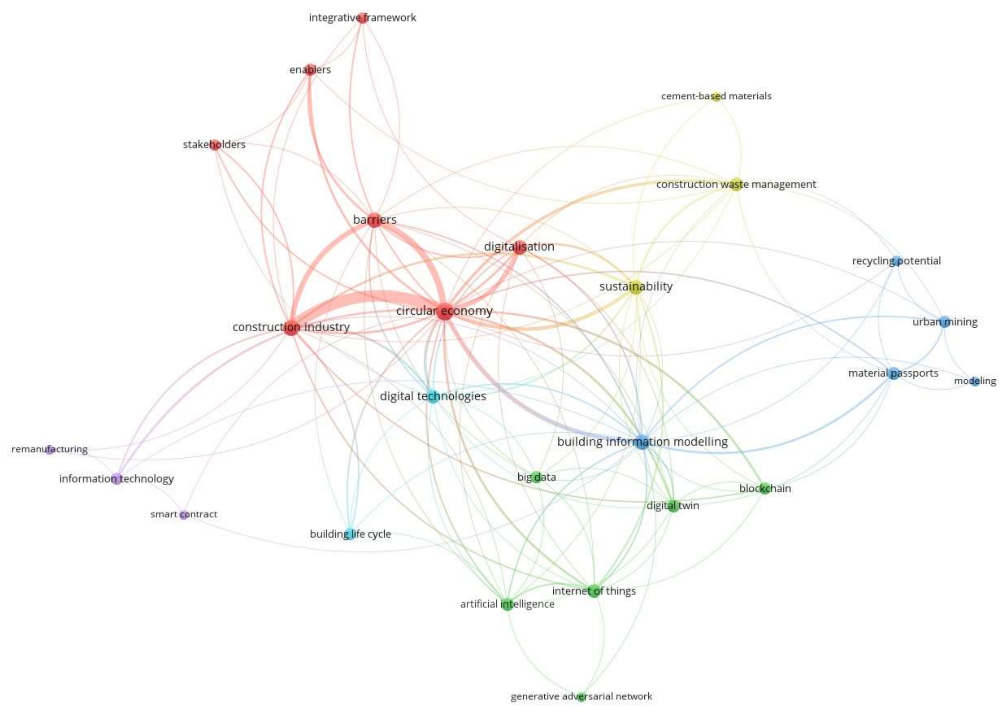
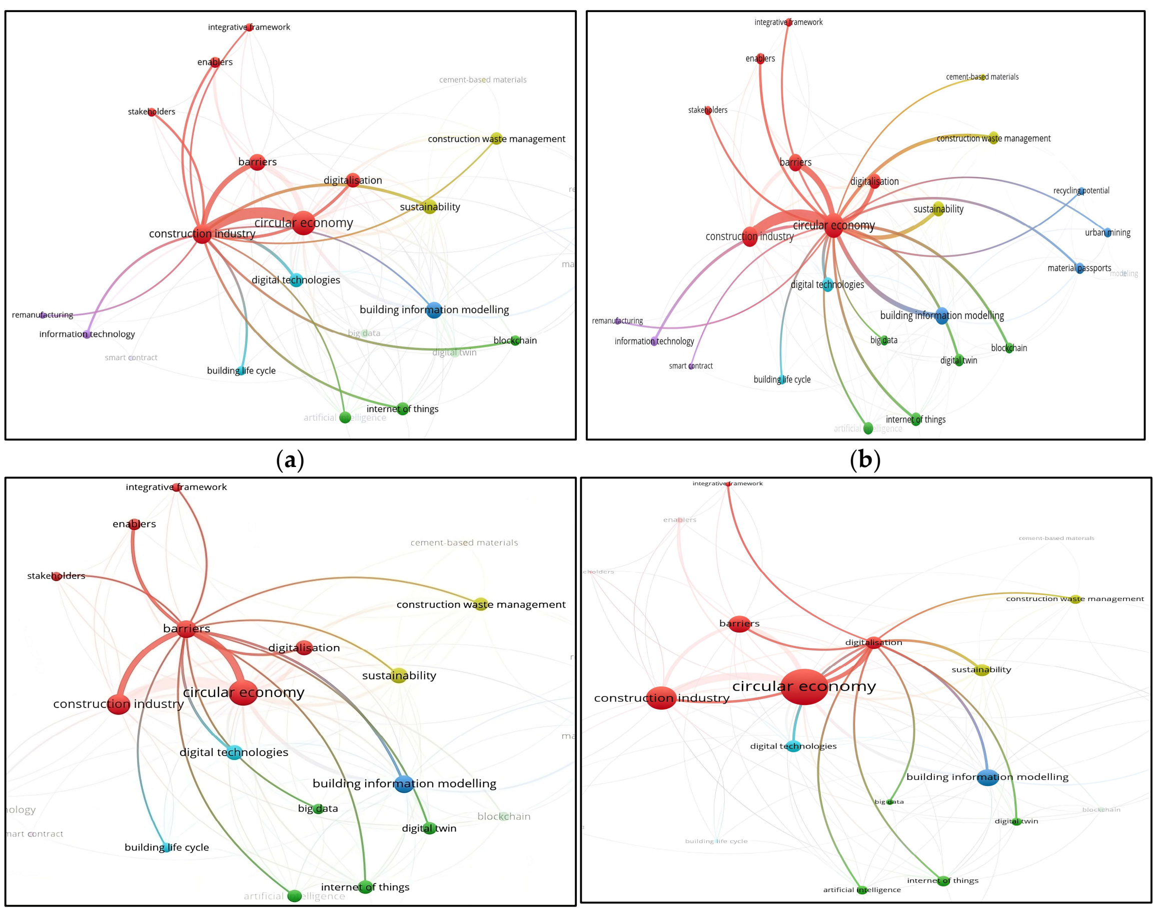


Figure 3. Map based on co-occurrence of keywords.



(**a**) (**b**)

(**c**) (**d**)

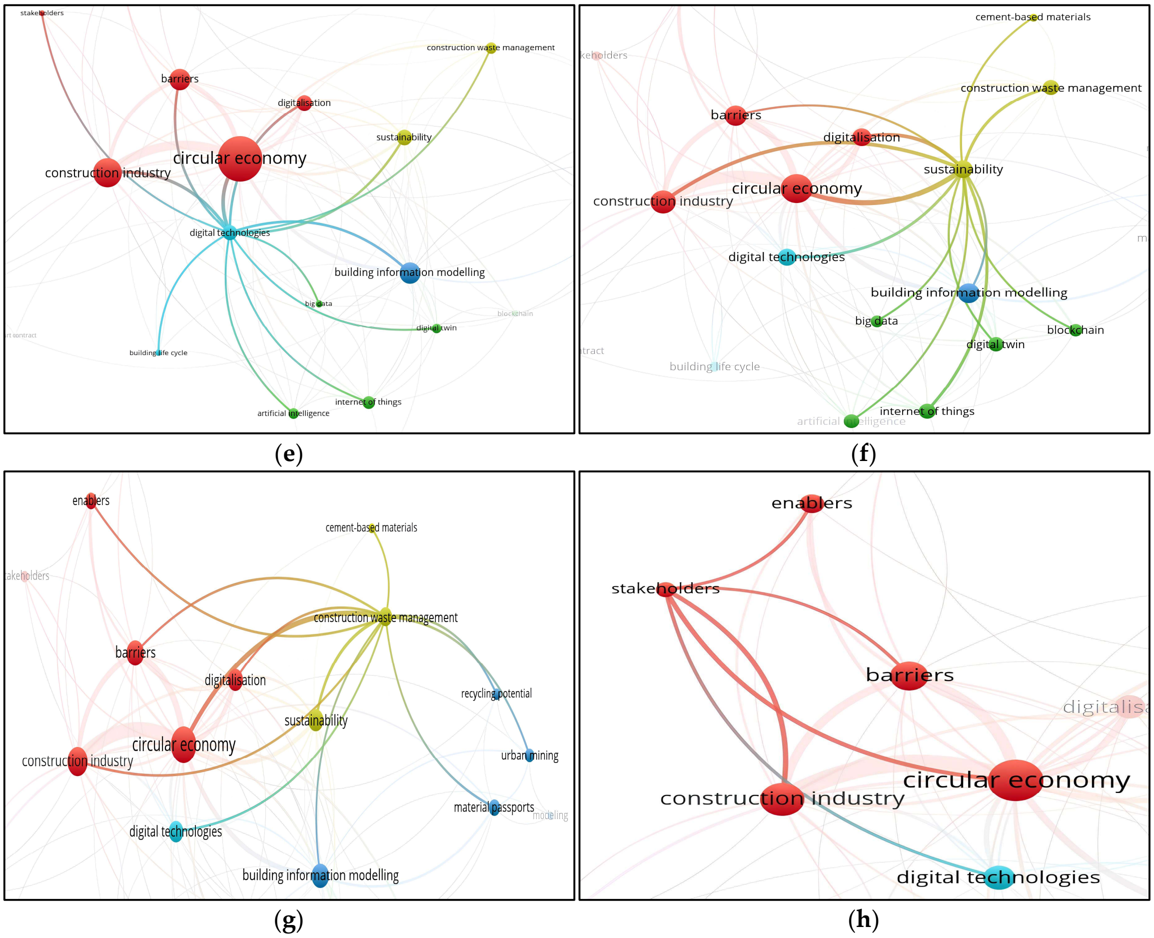


Figure 4. Illustration of interrelationships of (**a**) "construction industry", (**b**) "circular economy", (**c**) "barriers", (**d**) "digitalisation", (**e**) "digital technologies", (**f**) "sustainability", (**g**) "construction waste management", and (**h**) "stakeholders".

Figure 4a clearly illustrates the overarching domain of the node labelled "construction industry", while Figure 4b portrays the comprehensive scope of the node denoted "circular economy". These illustrations collectively emphasise the widely recognised DTs that the industry deems as adopting CE. Furthermore, the connections between the nodes in Figure 4c amply illustrate the implicit barriers that hinder the construction industry from utilising digital technologies to advance the circular economy. Figure 4d, e clearly show the existing relationships between DTs and the digitalisation process, along with the CE and construction industry. The construction industry is encouraged to embrace CE practices when digital technology and digitalisation processes approach their innovative level. Figure 4f depicts the current paradigm shift in the construction industry towards CE-based sustainability in forming a more resilient built environment. Additionally, a new relationship between "digital technologies", "digitalisation", and "construction waste management" is revealed in Figure 4g, demonstrating their significance in the management of construction waste. The node "stakeholders" is placed with the terms "circular economy", "barriers", "construction industry", and "digital technologies" in Figure 4h. This suggests that there is an increasing academic demand for steering the construction sector towards adopting a digital technology-enabled CE approach.

3.3. Barriers to Uptake of DTs to Implement CE in the Construction Industry

A total of 37 barriers to adopting DTs to implement CE in the construction industry were identified from the literature, which were further subdivided into 9 categories based on their characteristics, as shown in Table 2. Barriers are placed in an order where the frequency of each barrier category is positioned in ascending order.

Table 2. Barriers to implementing DT-enabled CE.

Barrier Category	Code	Barrier	Reference	Frequency
Organisational	A1	Lack of harmonised protocols and processes for data management	[27]	2
	A2	Need for new organisational role and training	[14]	
Infrastructure	B1	A lack of tracking mechanisms	[15]	3
	B2	A lack of expert circular networks	[15]	
	B3	Inadequate facilities for infrastructure	[15]	
Regulatory	C1	Lack of CE regulations	[1,3,4,9,22,25]	6
Standardisation	D1	Lack of standardisation for DTs	[3,9,13,17,22]	7
	D2	Lack of standardisation for recovered and reused materials	[1,8]	
Investment	E1	Lack of financial resources	[4,27]	12
	E2	Lack of financial incentives	[25,27]	
	E3	High implementation costs	[3,9,13,14,22,25,26,28]	
Nature of the Construction Industry	F1	Slow uptake of new technologies in the construction industry	[3,4,6,7,9,10,15,18,20,22,23,26]	21
	F2	Involvement of fragmented parties	[18,19,23,26]	
	F3	Lack of trained workforce	[7,14,15,28]	
	F4	Lack of CE-based knowledge management	[6]	
Technological	G1	Disposal of devices (technology disposal)	[3]	23
	G2	Elevated power consumption	[3]	
	G3	Sustaining the use of technology	[2,3,11,21,26]	
	G4	Lack of recognition for DTs	[10,22,24,25,28]	
	G5	Lack of integrated CDW processes, tools, and practices	[5]	
	G6	Lack of circularity in product design	[1,5,10]	
	G7	Absence of sufficient technologies for reusable, recycled, andrecovered materials	[1,5,8]	
	G8	Lack of proper information management systems	[2,5,7,10]	
Stakeholder	H1	Resistance to change	[3,4,9,14,24–26]	26
	H2	Lack of skills	[3,9,14,22,25]	
	H3	Lack of awareness	[4,7,14]	
	H4	Lack of commitment from stakeholders	[3,16,18,20,22,25,27]	
	H5	Cultural resistance	[18,23]	
	H6	Reluctance to adopt DTs	[22,26]	
Data Related	I1	Lack of built-environment-related data	[3,5–7,9,16,24,27]	35
	I2	Lack of clarity on the required data	[26,28]	
	I3	Data handling and management	[3,12,17,20,21,26,27]	
	I4	Poor-quality data	[3,5,13]	

I5	Unavailability of web-based database for secondary products	[5,15]
I6	Lack of data interoperability	[9,17,22,24–27]
I7	Absence of data standardisation	[14,20,26]
I8	Data security barriers	[3,4,9,22]

3.3.1. Organisational Barriers

These barriers are associated with a lack of commitment and collaboration from construction organisations and hinder the adoption of DT-enabled CE practices. These barriers are discussed in a detailed manner below.

Lack of harmonized protocols and processes for data management: Organisational harmonised protocols and processes for data management throughout the value chain in the circular economy context are still lacking [27]. The authors also stressed that the lack of regular organisational procedures and data management practices hinders information sharing among stakeholders, making applying the CE and material reuse difficult. Thus, a lack of harmonisation throughout the value chain impedes the adoption of DTs that enable CE in the construction industry.

Need for new organisational role and training: There is a tremendous need for new professional figures with competency in both information technology and building to aid in the development of a suitable path for the uptake of DT-enabled CE in the construction industry [14]. Additionally, new positions and operators with various responsibilities are required to support the professionals in reaching CE. Specialised training programs are needed to raise operators' skill levels to the required level for dealing with DT-enabled CE. The different supply chain stakeholders need to have transversal synergy [14]. There is an urgent need to hire new professionals for new technological-related roles within the organisation or provide existing professionals with the necessary training to meet technological demands.

3.3.2. Infrastructure Barriers

Infrastructure-related barriers that impede DT-enabled CE adoption in the construction industry are discussed below.

A lack of tracking mechanisms: A lack of tracking mechanisms appears as an apparent barrier that hinders recycling practices in the construction industry [15]. The implementation of CE principles necessitates tools for tracking to efficiently close the loop through recycling and reuse. Additionally, proper tracking of building materials offers data for informed decision-making to improve resource allocation and waste reduction practices. However, it is more difficult to identify and collect building materials from renovated or demolished structures without proper tracking, which results in a lack of obligation and can lead stakeholders to disregard recycling targets or regulations.

A lack of expert circular networks: Incorporating recycling to advance CE in the construction industry can be hindered by a lack of expert circular networks [15]. With the absence of strong expert networks, construction organisations might discover that it is difficult to obtain advice on how to successfully apply circular practices. In addition, the lack of expert networks makes it more difficult to implement new innovative circular solutions. To promote sustainable recycling practices in construction, it is essential to foster expert networks and enable knowledge sharing among experts in the field.

Inadequate facilities for sorting and monitoring systems: Circular practices in the building industry tend to be hampered by inadequate facilities for waste segregation and recycling infrastructure development [15]. Landfill waste increases because of inadequate infrastructure and restricted access to facilities for recycling. The absence of recycling infrastructure not only impacts the industry but also reverberates throughout broader society.

3.3.3. Regulatory Barriers

The lack of CE regulations, laws, and rules for adopting DTs to enable CE in the construction industry are discussed below.

Lack of CE regulations: There are several laws, rules, and conventions that apply to the construction sector, and they differ depending on the jurisdiction. The attainment of circularity in the building industry is impeded by the absence of government involvement in revising regulations and norms [4,25]. Inadequate laws for CE adoption and insufficient CE standards and guidance may cause regulatory obstacles. The [9] study also added that the construction industry may face regulatory challenges while utilising modern technologies for CE, including zoning laws, building codes, environmental restrictions, and other regulations. Furthermore, the authors have provided additional evidence to bolster their claims by referencing building codes that prohibit the use of specific recycled materials or restrict the application of particular construction techniques, as well as zoning laws that prohibit the construction of specific building types or place restrictions on the location of recycling facilities.

Regulatory obstacles may need to be addressed in the blockchain's application and execution for circular construction [3,22]. To adopt CE principles with the aid of DTs in the construction industry, the government must become involved in revising or amending existing building regulations and norms to comply with CE regulations. Otherwise, the contradictions and inconsistencies in these building regulations and standards could lead to misunderstandings and hinder the adoption of circular practices.

3.3.4. Standardisation Barriers

These barriers are related to the lack of standardisation, which hinders the application of DTs for the CE in the construction industry. They are described in detail below.

Lack of standardisation for DTs: The readiness for change will always provide an underlying conflict between the opposing demands of innovation and standardisation. Finding the ideal balance between the competing needs of innovation and standardisation can be critical to the construction industry's success in achieving circularity. A lack of standardisation can impede the advancement of DTs by undermining interoperability efforts and creating compatibility, security, and functionality problems. The construction industry's introduction of DTs, such as material passports, material databanks, and digital twins, is being slowed down due to a lack of standardisation, as noted by [3]. The implementation of circular economy practices in construction is not supported by adequate metrics, standards, or support mechanisms when digital technologies are implemented [13]. Integrating CE and BC in construction waste management is hampered by a lack of appropriate standards [22]. The construction industry lacks BIM standards and has a deficient contractual and legal framework [25]. Furthermore, it is difficult to standardise methods and procedures while integrating BIM with LCA [17]. Inconsistencies and inefficiencies in the construction value chain may result from the lack of standardisation for adopting these technologies, which may ultimately impede their adoption [9]. The construction industry must collaborate with industry organisations to develop and implement standardised protocols, covering various aspects of advanced technology adoption [9].

Lack of standardisation for recovered and reused materials: Recycled materials may provide uncertainties and practical issues if their performance is not guaranteed to be as intended [8], discouraging stakeholders from utilising them in construction projects. Stakeholders' uncertainty may arise from a lack of standards and limited practical guidance regarding recycled materials' application, efficacy, and durability. Further, the absence of standards for recovered materials is one challenge the building industry faces, making it challenging to modify existing designs [1].

3.3.5. Investment Barriers

These challenges are related to cost, financing, incentives, and investment, as discussed below.

Lack of financial resources: The primary rationale mentioned by construction companies for rejecting new implementations or improvements is a lack of financial resources and support. Researchers have highlighted that the primary obstacle to adopt digital technology in the building sector is the shortage of green finance and regulations at the corporate and governmental levels [4]. There is no denying that price is the primary factor when purchasing building materials. So, the high cost of retrieving and preserving the materials' residual value at the end of their useful lives makes virgin materials desirable for new projects [4].

Lack of financial incentives: The adoption of digital technology can be greatly impacted by a lack of financial incentives. Efficient reuse of construction materials and a CE will require large-scale data management. Data from existing structures and materials can be labour- and cost-intensive to gather, digitise, and manage [27]. Furthermore, the authors underlined that the absence of financial incentives is a significant obstacle to enabling efficient data management. It is challenging to develop a business plan for the large-scale reuse of construction materials without financial incentives from the government or the industry [27]. The absence of government financial incentives affects not only reuse but also the proper implementation of BIM [25].

High implementation costs: Using cutting-edge technology for CE in the construction sector can be costly and necessitate large infrastructural, software, and hardware investments. Aside from the cost of hardware and software, a significant financial cost is associated with the workforce's lack of knowledge and proficiency with digital technology [28]. The authors have drawn attention to the considerable implementation costs related to the use of BIM [25], blockchain, IoT, artificial intelligence (AI), big data analytics (BDA), material passports, and extended reality [3,9,22,28]. Moreover, these knowledge-intensive enabling technologies are associated with high R&D intensity, rapid innovation cycles, and high-skilled employment, resulting in substantial capital expenditures [14]. Moreover, DTs are becoming a niche area that necessitates convincing many organisational stakeholders to make investment decisions [26]. The construction industry is burdened by the upfront expenditures associated with its adoption [9,26]. However, the construction industry must carefully weigh the implementation's costs and expected advantages to ensure the investment is worthwhile. In the opinion of [14], choosing the genuinely effective technologies in an assessment of their whole life cycle necessitates the use of life cycle assessment procedures that emphasise the advantages (e.g., material savings) along with the drawbacks (e.g., the high energy consumption of DTs) of employing advanced technologies. However, financially fragile construction organisations may find it difficult to adopt new DTs because of the significant capital investment involved [13].

3.3.6. Barriers Associated with the Nature of the Construction Industry

These barriers examine the traits of the construction sector, including the slow uptake of new technologies, fragmented stakeholder involvement, lack of labour training, and CE-based knowledge management.

Slow uptake of new technologies in the construction industry: The construction sector is well known for its slow acceptance of new technologies [15,23,26] and has been the least digitalised in recent decades [7]. Industry appears to oppose technological advancement rather than waiting for an appropriate application of DTs. Also, how existing construction organisations function towards CE implementation reveals a lack of progress in digitalisation [4]. Thus, the construction industry may radically change if organisations successfully transition to digital circularity and encourage digitisation across all organisational levels [4,15]. Similarly, as discussed by [6], the construction industry lacks clearly defined indicators for integrating digital technology and CE. Furthermore, they noted that circularity technologies are still in their infancy within the industry. However, some authors argue that although DTs have enormous potential, there are insufficiently validated technologies and tools for construction-related CE [10]. The scalability challenges related to the application of blockchain technology for CE in the construction sector were also revealed by [22]. Although several cutting-edge technologies have demonstrated potential for promoting circularity, their scalability and applicability for larger projects or wider adoption may also be limited [9]. Thus, a thorough approach regarding both technical and economic factors must be considered to design scalable solutions to apply CE in the construction industry [9].

Involvement of fragmented parties: Researchers argued that the enormous number and dispersed nature of stakeholders involved in the construction industry are obstacles to improving construction industry practices [18,19,23,26]. The industry's split structure creates fragmentation among stakeholders at various project stages, increasing the likelihood of errors and poor interaction among these stakeholders, directly hindering the adoption of DT-enabled CE within the industry.

Lack of trained workforce: The adoption of DTs enabled CE implementation in the construction industry, which is severely hampered by the lack of skilled people on-site [6,14,28]. Furthermore, stakeholders involved in enabling technologies for CE implementation need to be highly knowledgeable and qualified [14]. The existing challenge for the organisations is to find highly skilled and knowledgeable stakeholders to collaborate on DTs-enabled CE projects.

Lack of CE-based knowledge management: In their study, [6] found that the industry lacks efficient knowledge management systems, making deploying DT-enabled CE in the construction industry difficult. It is clear that an organisation suffers greatly when CE-based knowledge is lacking, and significant time is lost looking for pertinent information rather than finishing tasks with an established goal.

3.3.7. Technological Barriers

These barriers are caused by technological constraints that restrict the appropriate application of digital technology to implement CE in the construction industry.

Disposal of devices (technology disposal): Disposal of technology raises issues as it may have a negative effect on sustainability goals and the environment, either directly or indirectly. There are concerns regarding the disposal of technology, which will directly or indirectly impact the environment and cause negative achievements in sustainability. IoT devices' effects during their disposal raise concerns, even though their deployment helps to enable circularity in construction [3]. Furthermore, the authors also emphasised the issues with sustainability caused by the manufacture and disposal of extended reality technology.

Elevated power consumption: The utilisation of digital technology to promote circularity raises questions because of the high-power consumption it requires to operate. Blockchain usage necessitates a sizeable computational power [3]. Thus, the high electricity consumption of IoT has been highlighted by authors, as another negative environmental impact.

Sustaining the use of technology: These barriers are associated with MPs, BIM, AI, digital twins, IoT, BDA, and RFID. MPs are intended to monitor material flows throughout the life cycle of buildings and record material documentation that will facilitate the recovery of materials for reuse during the renovation and demolition phases. However, there is a requirement for manual updates each time a building undergoes modification, which remains a significant barrier to the practical implementation of MPs [26]. Additionally, incomplete information poses a significant obstacle to the effective compilation of an MP [11]. Initially, BIM enhanced design quality by combining all pertinent data from several disciplines into a single model. In contrast, BIM provides a means of smoothly incorporating circular economy concepts into building projects. Concerns about BIM software's frequent updates and changes to newer file formats have been raised, possibly rendering

BIM models incompatible [26]. The success of every AI model or project heavily depends on the labelled data, known as training data, which are used to teach machine learning algorithms or models to make the right decisions. The AI models are highly susceptible to biases resulting from the training data [26].

Furthermore, researchers highlighted that the complexity of the code makes it very challenging to create a rule-based program [21]. Circularity in the construction is expected to be made feasible by DT, which connects real-world data with digital data. Even though DT and CE are a combination, the capacity of a system to carry out its intended function over an extended period consistently and without failure is referred to as reliability. Reliability is an essential consideration in the context of the IoT, as problems with malfunctioning devices may have serious consequences [3]. BDA has become vital to producing insightful information for circular construction decision-making. BDA calls for intensive analysis to extract valuable information from vast data [3]. One of the existing obstacles to utilising RFID is the lack of technological and functional knowledge, which determines where the RFID tag should be installed [2].

Some researchers have highlighted that RFID tags have a shorter service life (15–20 years) compared to construction components. It is also clear that a significant gap exists since stakeholders have limited time to manage an asset during its useful life. Stakeholders' interest in RFID is significantly curtailed when an asset is transferred to the user after it has been sold or the warranty has ended. Even though DTs pave the way for circularity in construction, the issues related to those technologies make it challenging to sustain their benefits.

Lack of recognition for DTs: A new paradigm can be adopted more quickly and easily if the technology and information are accessible to advance it [7]. DTs were not recognised in the circular construction due to the lack of knowledge and understanding related to them [28]. Furthermore, the absence of a vital ICT infrastructure in the construction sector prevents DTs from being used diligently [24]. Construction organisations are rushing to embrace DTs to demonstrate their social responsibility without having a firm grasp and awareness on them. The adoption of CE is hampered by the construction industry's poor technological and eco-innovation ability and immaturity in enabling DTs and solutions [10,22]. Despite BIM's widespread use, some stakeholders remain with limited awareness and knowledge [25]. In addition, they have emphasised that the lack of maturity of CE in the construction industry led to a shortage of investment in tools and technologies necessary for CE adoption. The underappreciation of DTs reflects the double-barrelled impact of change aversion on CE adoption [10]. In the modern digital age, recognising the opportunities presented by digital technology has become essential for competitive survival. It is imperative to acknowledge the role of DTs in the construction industry to enable circularity in construction.

Lack of integrated CDW processes, tools, and practices: Although several studies have highlighted the potential for digital technology to support integrated construction and demolition waste management (CDW), there are still insufficient integrated CDW procedures, tools, and practices. The industry still lacks tools for detecting, categorising, and certifying salvaged materials [5].

Lack of circularity in product design: Lack of material alternatives available in the industry inhibits product design growth [1]. Furthermore, increased supply chain complexity lessens the circularity of product design. Construction circularity is delayed by ineffective green building design development [5]. The practical use of design for deconstruction (DfD) is hindered by a lack of standard spatial geometries and limited visualisation in this context [5]. Ref. [10] emphasised that insufficient technologies are available to design for a building material's end of life.

Absence of sufficient technologies for reusable, recycled, and recovered materials: The current state of recycling technology is immature and stems from a lack of technological advancement that is necessary for the appropriate recycling of materials [8]. Inadequate material separation, administrative obstacles, and a deficiency in making readily disassembled goods hinder recycling procedures [5]. Complications with material recovery at the end of life are another technological barrier to the implementation of CE [1]. Insufficient technological capabilities for managers to recover and reuse resources is a significant barrier impeding circularity [8].

Lack of proper information management system: The absence of an information management system was linked to the lack of transparency and availability of technical data on construction elements, extending the gap to the current modelling tools and material database [5]. Furthermore, there are still insufficient databases and information on constructing, particularly at the end of life, due to the restricted number of existing CE-oriented databases [6]. The limited availability of information that aligns with the end of life has impeded the adoption of digital technology for circular buildings. A significant quantity of data and information may be needed for circular solutions about inventory, management, and asset end-of-life [2]. Still, it is not easy to track recycled materials using trustworthy information systems [10].

3.3.8. Stakeholder Barriers

Stakeholders are groups of individuals who have the potential to influence the objectives of an organisation, its progress, and even its existence. This set of barriers delves into the stakeholders' unwillingness to adapt and their inadequate engagement, knowledge, and understanding of using DTs to enable CE.

Resistance to change: The resistance-to-change mindset among the stakeholders who are used to traditional construction processes is one of the most significant barriers to the adoption of new technologies for CE in the construction industry [3,4,9,14,24,26]. Construction stakeholders are typically conservative in the context of early acceptance and diffusion of technological innovation [24]. Stakeholders' perceptions are influenced by ease of use and technology acceptance, which discourages them from adopting DTs at this early stage [4]. A familiar problem stakeholders face is figuring out how DT-enabled CE may help the construction industry by cutting waste and increasing productivity [9,14]. BIM, GIS, and RFID are the contemporary ICT-based decision-making tools currently utilised in the construction industry [24]. However, industry stakeholders have not yet widely used IoT, big data, and blockchain, potentially boosting the practice of CE in the construction sector. Ref. [3] also highlighted the limited adoption rate of material passports and material databanks among industry stakeholders. As per [26], respondents acknowledged that even if they obtain BIM models from architects, they still prefer using 2D drawings for their jobs. Since executive support and client demand for adopting BIM are lacking, there is a general resistance to change [25]. Furthermore, some participants in the [26] study highlighted that although new technologies have been implemented in their organisation, some colleagues might be hesitant to use them since they have been using the same programs and processes for a long time. In the [14] study, participants highlighted the possibility of losing their professional identity because of the industrialisation process made possible by specific technologies. Moreover, with the introduction of digital technology, stakeholders believe they will be integrated into the industry as technicians, frequently offering less flexibility and income than the free profession. Stakeholders prefer to adhere to the status quo, as more significant penalties and a lack of high-tech expertise are associated with project delivery failure [24]. Even though several ICT-based decision support tools have been developed to aid in the implementation of CE, it is not easy to persuade stakeholders that developing innovative CE business models is essential to surviving in the resource-intensive market of the future [24]. A change in the attitudes and behaviours of the participants is necessary for the transition from linear building to DTs, enabling circular construction.

Lack of skills: The advent of digital technology may have created a skills gap in the industry, which could restrict the use of these resources to advance CE in the construction industry [9]. Utilising DTs for CE in the construction industry demands stakeholders with specific data handling, programming, and analysing expertise. The research by [3] noted that stakeholders in the construction industry lack the technical know-how to create and apply AI models. In addition, the authors confirmed that specific equipment and stakeholder skills are required to reap the full benefits of extended reality technology. The authors also emphasised that the lack of BIM knowledge, skills, and experienced workers in the construction sector hinders the wider application of BIM [25]. Inadequate expertise in digital technology leads to a lack of competency necessary for managing technological implementations like blockchain [22]. Furthermore, a lack of experience among stakeholders raises concerns about the practical commitments that come with technological progress [14]. Thus, the industry faces a significant skills gap that appropriate solutions must address.

Lack of awareness among stakeholders clients, and the public: Stakeholder awareness and engagement are the key factors that facilitate a seamless transition from linear construction into a circular one. Lack of understanding among stakeholders and clients is the most significant obstacle impeding the shift to DT-enabled circular construction [4,6]. Stakeholders must become conscious of the environmental impacts created by the construction industry and urge circular principles by changing their disposal-focused and cost-driven perspectives. The study conducted by [7] highlighted that the public ignores the advantages and practices of CE without sufficient knowledge. Hence, inadequate client and public awareness of CE processes and benefits is one reason why constructions still adhere to linear construction processes. A lack of awareness about DTs enabled CE in the construction industry, which can also be interpreted as deliberate ignorance or failure to learn or change. It is imperative to raise awareness of DT-enabled CE and demonstrate its advantages for the economy and environment to encourage stakeholders, clients, and the public to embrace DT-enabled CE practices. Stakeholders, clients, and the public may lose the chance to produce more circular results if they lack the necessary knowledge and comprehension. The public, clients, and stakeholders must change their viewpoint and admit that they are hindering the implementation of CE. Additionally, stakeholders in the construction industry are not even aware of the advantages new technologies can provide [7,14].

Lack of commitment from stakeholders: A significant obstacle remains the absence of stakeholder cooperation and communication [3,18,22]. Furthermore, gathering project-related data to support circular construction is challenging as the industry is so dispersed [3,16]. The inability of many stakeholders to collect, handle, share, and manage data regarding building materials and recognise information's worth in embracing circular principles is an additional barrier to data management [27]. Demanding the construction community's shared commitment to data integration throughout the value chain is one of the most significant barriers [20]. Stakeholders' unwillingness to exchange information amongst themselves and with other parties in the value chain hampers data management and material reuse in the AEC industry [27]. Moreover, there are still issues with unclear roles and responsibilities, poor communication, and a lack of teamwork in the BIM implementation process [25]. Due to their unwillingness to cooperate, AEC industry stakeholders cannot support the circular economy. There is a substantial chance of failure when implementing any CE program without significant collaboration from the key stakeholders.

Cultural resistance: The expected values, beliefs, and norms that shape stakeholder behaviour and their work process are called culture. Adopting new technology within organisations is hampered by existing cultural behaviour, which necessitates systemic transformation [26]. Stakeholders must adopt new attitudes and behaviours that modify the construction industry's culture to enable the transition from linear to circular construction. However, such a significant change is challenging to implement in the sector where adopting supply chain fragmentation and hesitant technology are typical [26]. According to [22], cultural variations in the construction industry also impact the adoption of new technologies like blockchain. Cultural variances and technological advancements influence one another's growth.

Reluctance to adopt DTs: Employees are unlikely to embrace new technology unless their work environment encourages creativity, cooperation, and a readiness to change. The study by [26] showed that a full implementation of DTs in daily operations is needed for both digitalisation and CE, which are currently limited to pilot projects and the company's corporate vision. Ref. [22] states that organisations typically oppose using DTs in favour of maintaining the status quo. Organisational resistance makes a company rigid and unable to adjust to internal or external demands for change.

3.3.9. Data-Related Barriers

These are the barriers related to the lack of quality, quantity, nature, and management of built environment-related data. The most significant data-related obstacles found in the literature are the lack of built-environment-related data, lack of clarity on the required data, poor data handling and management, poor-quality data, unavailability of web-based databases for secondary products, lack of data interoperability, and absence of data standardisation and data security barriers, which are discussed below.

Lack of built-environment-related data: One of the main concerns regarding adopting the DT-enabled CE is the absence of relevant data from the construction industry. Large volumes of data are required to efficiently operate advanced technologies like deep learning, BDA, and machine learning [3,5,7,9]. The scarcity of data sets makes it challenging to enable AI models for systemic circularity in the construction industry [6]. Furthermore, there is still a lack of technology applications focused on CE due to the shortage of comprehensive databases [7,24]. It is challenging to gather project life cycle data to support circular construction [16]. Ref. [6] pointed out that there is still a shortage of data about the end-of-life stage, emphasising how little focus is placed on it. Furthermore, the authors stated that data and information for prediction in a CE are not easily accessible everywhere in the world for appropriate demolition auditing. However, lack of documentation of the materials used in construction is a typical occurrence in the industry, but this hinders the materials' reusability in the future [5,27]. Additionally, the sector lacks critical information for prediction and disassembly, which is imperative for an effective deconstruction process [7]. Data about building materials and supplies are frequently absent, incomplete, inaccessible, or not digitalised, which is one of the significant issues of the modern industry [27]. The absence of defined methods for collecting and storing data in the construction sector leads to a lack of data availability, complicating the adoption of cutting-edge technology [9]. Moreover, ownership, access, privacy, and trust-related problems within the industry contribute to a shortage of data [5]. There is still plenty of work to be carried out regarding data collection, processing, and reprocessing to create meaningful information, and ongoing data recording is needed to support decision-making [16]. Data are crucial to the application of circular practices throughout the whole life cycle of each construction project. A lack of data from the project may miss the opportunity to create more circular and profitable outcomes; Ref. [7]. If efforts are not made to address the data issue, future research on DT-enabled CE may be misdirected.

Lack of clarity on the required data: Uncertainty about the requirements for circular strategies contributes to a lack of built-environment data [26,28]. BIM provides a database for MP generation and facilitates data sharing between project stakeholders to allow CE. However, there are uncertainties regarding data requirements for generating MPs [26]. Due to the lack of fully defined DT standards, data requirements cannot be appropriately specified [28]. More efforts must be undertaken to critically assess stakeholders' data requirements to enable them to make informed decisions on CE [26]. Stakeholders lack the expertise to evaluate what technologies should be developed and what data they might need to promote circularity in the construction sector. Lack of clarity on the required data barrier must settle down as soon as possible to reap the DT-enabled CE implementation benefits.

Data handling and management: Data handling and management of collected data appear to be a prominent barrier to CE implementation as technologies such as AI, IoT, and BDA require and rely on large quantities of data for their functioning. BDA offers a variety of solutions and forecasts for the future by combining all other technologies, including BIM, AI, and IoT [3]. Enabling circularity requires the management of varied data over the whole life cycle. Data are produced at each construction phase from various sources, such as sensors, monitoring equipment, and BIM [3]. While the integration of life cycle assessment (LCA) and BIM offers significant opportunities, managing complex data is undoubtedly challenging [17]. Moreover, it leads to challenges in data handling related to accessibility and assessment, which necessitates a substantial time and financial commitment [20–22]. DTs and solutions facilitate the open, transparent, and standardised sharing and connecting of data across the various stakeholders in the supply chain. So, a proper data management mechanism is a critical problem for DT adoption, especially for MPs [26]. Also, coordinating data management for material reuse without clear standards is challenging in the construction industry [27]. The implementation of blockchain is still beset by challenges with data gathering and transparency [12].

Poor-quality data: Data of inadequate quality cannot meet the purposes for which it is being used. Low-quality data can erode trust in shared information due to insufficient coverage, disparate data formats, random collection practices, and monitoring [5]. Additionally, the writers stressed that issues with ownership, access, privacy, and trust in the sector could potentially hinder the acquisition of high-quality data [3]. They highlighted the need for vast quantities of high-quality data for DTs to operate as intended. The vast quantity of data gathered for DT operations cannot be guaranteed to be of high quality [13]. The quality of the data input influences the BIM outcome [3]. The authors also highlighted how poor construction data quality impedes using BDA. Poor-quality data lead to inefficient decision-making and reduced opportunities for maximising CE.

Unavailability of web-based databases for secondary products: According to circular principles, secondary products must have an extended life until they reach a point at which they can no longer be utilised. There is a lack of documentation in the management of used building materials, which raises concerns about their ultimate circularity [5]. Furthermore, inadequate material property information for materials listed on a web marketplace typically discourages stakeholders from purchasing them. The exchange of usable secondary materials and products is hampered by the lack of an efficient CE web-based waste exchange system [6]. Moreover, reusing secondary materials through marketplaces raises the issue of meeting quality requirements, as measuring the physical quality of secondary products is tedious and requires expert inquiry [6]. As a result, the lack of a web-based database for secondary products deters potential users from considering them for further purposes.

Lack of data interoperability: The transmission of information between stakeholders along the value chain is hampered by data being frequently kept in disparate repositories, in disparate forms, with differing degrees of ownership and accessibility [27]. Data transparency is believed to be necessary to facilitate interoperability [27]. Integrating advanced CE technologies with current systems or technologies might be challenging. It is not easy to configure these technologies to ensure process and data interoperability for diverse stakeholders within the industry [9,24].

Additionally, the authors noted that BIM model versions vary since the software is frequently updated and that future compatibility issues may arise with newer file formats [25,26]. As per [22], their incompatibility could significantly hinder amalgamating concepts such as CE, blockchain, and construction waste management. Furthermore, they added that there is a need for a proper system conversion to reap the benefits of blockchain-enabled CE [22]. It is difficult to ensure technological interoperability between LCA and BIM technologies [17]. Interoperability and data sharing are difficult to achieve while using various DTs based on disparate languages and standards [26]. Moreover, the authors emphasise the importance of incorporating digital technology into existing systems. A multifaceted strategy involving technical solutions, teamwork, and a long-term outlook is needed to address the issue of lack of interoperability [9]. Ineffective data management can be caused by a lack of technical interoperability, which can slow down the construction industry's practices of reusing materials [27].

Absence of data standardisation: Inconsistencies and inefficiencies in the construction value chain may result from the lack of standardisation for adopting these technologies, which may ultimately impede their adoption [9,14]. The absence of standardisation presents a significant obstacle to the construction industry's adoption of cutting-edge technologies for CE. Furthermore, researchers noted that the lack of a national standard for data exchange is becoming an issue for stakeholders [26]. Consequently, international data standardisation may resolve these issues with data sharing and administration. This requirement for standardisation and open interfaces is a significant barrier to the construction community's commitment to data availability [20]. The construction industry must collaborate with industry organisations to develop and implement standardised protocols covering various aspects of advanced technology adoption [9].

Data security barriers: Digitisation presents a complicated cyberspace network, making industries vulnerable to cyberattacks despite its apparent benefits. The fragmented nature of the construction sector, where different stakeholders have varying requirements for data privacy and security, has always presented significant hurdles in this regard [9]. The construction industry has witnessed a surge in cyber risks, making the infrastructure for cyber security imperative for all organisations [4]. Nowadays, blockchain is frequently utilised in the construction sector for CE-related solutions, which creates privacy or security concerns and legal liabilities [3,22]. Furthermore, ref. [3] stated that data security is required as complete building data are included in material passports and data banks.

Additionally, DTs are highly susceptible to privacy issues caused by cyberattacks [3]. Since these technologies include collecting, storing, and exchanging sensitive data, implementing them to promote CE in the construction sector may present significant difficulties [9]. Formulating data privacy and security guidelines and measures to safeguard sensitive data are critical areas for future growth in this discipline [9].

3.4. Barrier Category Frequency Analysis

This study identified thirty-seven (37) barriers that hinder the construction industry from adopting digital CE, and they are categorised into nine (09) primary barrier categories, as shown in Table 2. The most frequently identified barriers under each category are presented in Figure 5.

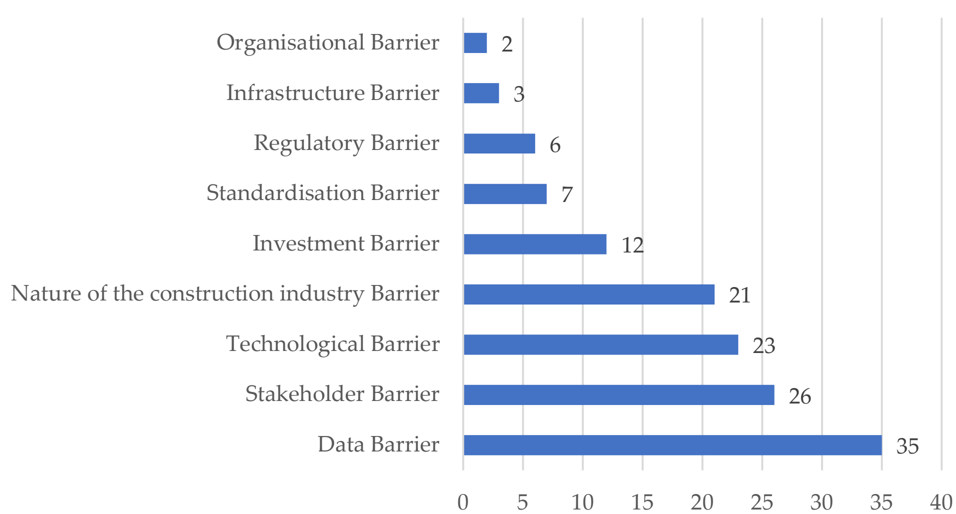


Figure 5. Category-wise representation of CE barrier frequencies.

Out of all these barriers, data-related barriers were the most observed, with a total count of thirty-five occurrences in the literature. In contrast, technological barriers were noted twenty-three times, indicating the significance of the transition. Stakeholder barriers were encountered in twenty-six instances, and organisational barriers were mentioned two times, revealing how their change-averse mindset and actions hindered the circular transition. A key barrier to circular transformation is the nature of the construction industry, which has been pointed out twenty-one times in the literature. The investment barrier was observed twelve times in the literature, which is a significant impediment that hinders the circular transformation in terms of economic parameters. Regulatory barriers appeared six times, highlighting the ways in which various aspects of the application of digital technology are impacted by limitations imposed by laws or policies. Standardisation barriers appeared seven times in the literature, demonstrating how insufficient standardisation influences the uptake of digitalised CE. Finally, an infrastructure barrier was encountered three times, indicating that insufficient infrastructure development capabilities impact the advancement of circularity.

3.5. Pareto Analysis

The critical impediments must be prioritised to ensure effective resolution; merely identifying them is inadequate. Pareto analysis was used to further examine thirty-seven barriers under nine taxonomies to provide decision-makers, policymakers, and industry practitioners with more insightful information. The "80/20" rule is a heuristic derived from the Pareto principle, which states that about 80% of the effects come from 20% of the causes for many occurrences. When striving to enhance a transition, the Pareto principle is an excellent tool for focusing attention on the crucial few resources responsible for most issues. Since the overall (cumulative) frequency equals 100%, the "trivial many" barriers only account for 20% of occurrences. In comparison, the "vital few" obstacles represent a significant portion (80%) of the cumulative percentage of citation frequencies. Based on Pareto analysis, the barriers resulting in cumulative citation frequencies of 80% are deemed the most crucial. The following Figure 6 shows the results of the Pareto analysis for the identified barriers.

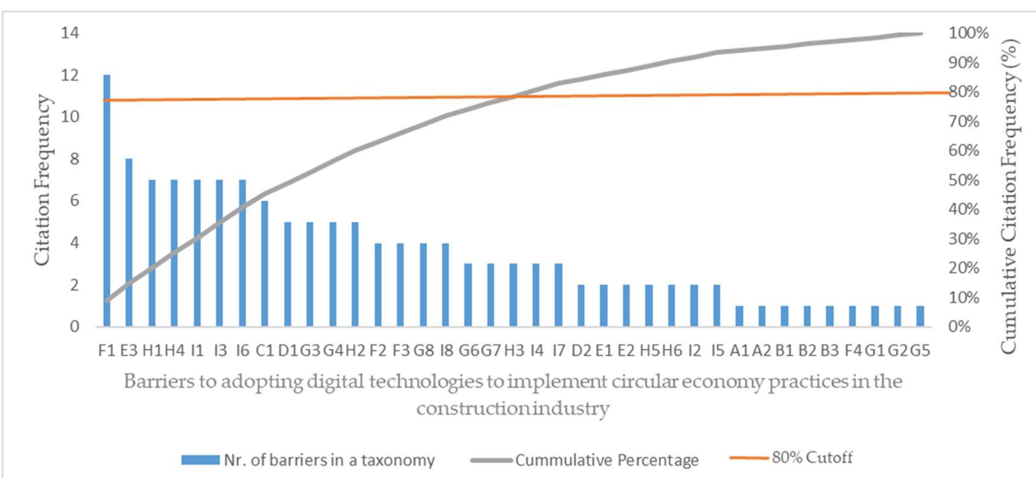


Figure 6. Pareto chart for identified barriers. The cumulative total is represented by the grey-colored curving line, and the cut-off line is the orange line that strives through 80%.

According to the Pareto analysis, slow uptake of new technologies in the construction industry (F1), high implementation costs (E3), resistance to change (H1), lack of commitment from stakeholders (H4), lack of built-environment-related data (I1), data handling and management (I3), lack of data interoperability (I6), lack of CE regulations (C1), lack of standardisation for DTs (D1), sustaining the use of technology (G3), lack of recognition for DTs (G4), lack of skills (H2), involvement of fragmented parties (F2), lack of trained workforce (F3), lack of proper information management systems (G8), data security barriers (I8), lack of circularity in product design (G6), absence of sufficient technologies for reusable, recycled, and recovered materials (G7), and lack of awareness (H3) are considered as vital barriers.

4. Discussion

This study aimed to determine the barriers to adopting DTs to implement CE practices in the construction industry. The long existence of the construction industry, which is a highly resource- and energy-intensive sector, has resulted in the depletion of natural resources and the vast production of waste, both of which cause greenhouse gas emissions, which are unquestionably the primary cause of climate change. Furthermore, the industry's current state endangers the ecosystem's ability to support future generations and exacerbates ecological issues [8]. Studies like [4,6,14] reveal that the construction industry follows the linear economic model, and it must shift into a circular economy to ensure the sustainable use of resources and energy.

Thus, the CE became a catalyst for addressing issues like biodiversity loss and climate change, improving the use of limited resources, and reducing emissions. The findings from [6] have revealed that the fundamental objective of systemic circularity in construction entails making sure that the product system for buildings is well planned, circularly designed, and has the essential reverse cycles, system conditions, and business models to ensure the seamless reusability of building materials at the end of life. Therefore, different CE initiatives such as building information modelling, urban mining, secondary materials markets, deconstruction design, and construction and demolition waste (CDW) hierarchy are moving in distinct directions [5], which requires innovating their production and consumption along with DTs [14].

It is challenging for construction organisations and other important stakeholders to integrate strategies that ease the shift to CE [1]. The construction industry's initial adoption of CE has exposed implementation difficulties, prompting the search for an enabler to facilitate the proper adoption of CE practices throughout the industry. The dawn of DT with the fourth industrial revolution shows its potential to enable CE in other sectors. It attracted the attention of academics who wanted to explore the possibility of DTs in CE implementation for the construction industry. Similarly, DTs have been identified by [2–4,6,9,14,16–24,26,28] as value-creating and collaborative tools that can potentially influence the construction industry's capacity to realise CE significantly.

Information and communication technologies (ICT) are acknowledged as possible solutions to address wicked CE concerns as they can assist with CE-oriented decision-making [24]. By utilising a multiple case study with three social housing organisations at the forefront of circularity implementation in the Netherlands, ref. [26] investigated how large-scale social housing organisations use DTs in their circular new build, renovation, maintenance, and demolition projects, as well as the barriers they encounter. Ref. [26] validated that even if DTs have a promising future, several important implementation-related issues still need further research. However, the problem of how various obstacles impede the use of DTs that enable CE in the construction industry is still unexplored.

The current study fills this research gap by identifying the barriers that hinder digital technology-enabled CE adoption in the construction industry. A specific search string was utilised in the Scopus and Web of Science databases to find pertinent publications by adhering to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses. A total of 377 articles were extracted from the database and subsequently subjected to a full-text review following an initial screening of the titles, abstracts, and keywords. Ultimately, twenty-eight papers were incorporated to identify barriers affecting the adoption of DTs that enabled CE within the building sector. Thirty-seven barriers hindering the adoption of DT-enabled CE in the construction industry were identified and grouped into nine broad categories: organisational, infrastructure, regulatory, standardisation, investment, nature of the construction industry, technological, stakeholder, and data-related barriers.

The construction organisations' lack of harmonized protocols and processes for data management and insistence on new organisational roles and training demonstrate their inattention to embracing DTs that enable CE. Furthermore, the industry's inadequacy in developing proper recycling and waste separation infrastructure impedes the adoption of DT-enabled CE. The absence of clear regulations severely hampers the industry's adoption level of DTs and CE. Even though the sector accepts digital technology and recovered and reusable materials, the absence of standardisation is delaying the development of CE. Implementing DTs for the better application of CE in the construction industry requires higher implementation costs, while industries struggle with a lack of financial resources and incentives. Moreover, the construction industry's slow uptake of new technologies with a fragmented and lack of trained workforce limits the proper adoption of DTs for the uptake of CE.

Disposal of devices, elevated power consumption, sustaining the use of technology, lack of recognition for DTs, lack of integrated CDW processes, tools, and practices, lack of circularity in product design, absence of sufficient technologies for reusable, recycled, and recovered materials, and lack of proper information management systems are the technological implications that arise with the implementation of DT-enabled CE in the construction industry. Further, the barriers limiting implementation from a stakeholder perspective include a lack of skills, awareness, and commitment; cultural resistance; unwillingness to embrace digital technology; and resistance to change. Finally, the data-related barriers that interrupt the uptake of DT-enabled CE are a lack of built-environment-related data, a lack of clarity on the required data, data handling and management, poor-quality data, the unavailability of web-based databases for secondary products, a lack of data interoperability, the absence of data standardisation, and the existence of data security. Determining suitable strategies for the existing barriers in the construction industry that impede the adoption of DTs that facilitate CE execution is crucial.

The primary knowledge gained from this study was that it identified several types of barriers hindering the implementation of DT-enabled CE in the construction industry.

5. Conclusions

This study comprehensively investigated the barriers to adopting DT-enabled CE in the construction industry by employing a systematic literature review using the PRISMA protocol to search, evaluate, and extract metadata. This study includes twenty-eight (28) papers obtained from Scopus and Web of Science databases. A thorough understanding of the barriers to adopting DTs enabling CE in the construction industry was achieved via the review of this research. This study identified thirty-seven (37) barriers, and they were categorised into the following nine areas: organisational, infrastructure, regulatory, standardisation, investment, nature of the construction industry, technological, stakeholder, and data-related barriers.

The vital barriers hindering progress in CE in the building sector were identified through a Pareto analysis. These vital barriers include slow uptake of new technologies in the construction industry (F1), high implementation costs (E3), resistance to change (H1), lack of commitment from stakeholders (H4), lack of built-environment-related data (I1), data handling and management (I3), lack of data interoperability (I6), lack of CE regulations (C1), lack of standardisation for DTs (D1), sustaining the use of technology (G3), lack of recognition for DTs (G4), lack of skills (H2), involvement of fragmented parties (F2), lack of trained workforce (F3), lack of proper information management systems (G8), data security barriers (I8), lack of circularity in product design (G6), absence of sufficient technologies for reusable, recycled, and recovered materials (G7), and lack of awareness (H3), which requires more attention. Still, organisational, infrastructure, regulatory, standardisation, investment, nature of the construction industry, technological, stakeholder, and data-related barriers to implementing DT-enabled CE in the construction industry require proper solutions.

The research outcomes offer significant perspectives that aid in identifying barriers, enabling construction professionals, companies, and policymakers to formulate more efficient approaches for the successful integration of technology enabled CE implementation in the construction industry. Moreover, the study's findings contribute to developing more circular built environments. The study's scope is limited to data collected from the literature, and expert opinions from CE experts were not consulted for validation. Also, the papers included in this research were limited to the papers published on Scopus and Web of Science databases until March 2024.

Due to the broad application of DTs, future research directions can be proposed based on the findings of this study, as follows: Firstly, the study could be conducted with specific DTs by incorporating CE experts' expert opinions to validate the results. A second worthwhile study for future scholars would incorporate experts' opinions and discussions to illustrate the various barriers identified for the progression of DT-enabled CE. Furthermore, future works could consider identifying appropriate strategies to overcome these identified barriers and successfully implement DT-enabled CE in the construction industry. Furthermore, this research highlights the necessity of undertaking further research on digital infrastructure and their impact on circular economy implementation in the construction industry; how construction companies can formulate their strategies to align digital adoption with circular economy principles; the current regulations affecting the adoption of digital technologies based circular practices in the construction industry; policy frameworks and regulations pertaining to the execution of digital technologies; and the establishment of comprehensive digital platforms that facilitate communication, data exchange, and cooperation among construction stakeholders by connecting them across the value chain. Furthermore, it is necessary to undertake further studies on the development of an appropriate tool to identify, classify, and verify salvaged construction materials; stakeholders' perspectives on the risk factors that are associated with digital technology and create strategies for mitigating those risks that are unique to circular construction; and strategies to improve the compatibility of disparate data sources and formats and create standardised protocols to facilitate the exchange of data between various platforms and stakeholders.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16083185/s1, PRISMA Statement [31].

Author Contributions: Conceptualisation, S.T., N.U., G.K., and R.A.-A.; Methodology, S.T. and N.U.; Software, S.T.; formal analysis, S.T. and N.U.; writing—original draft preparation, S.T.; writing—review and editing, S.T., N.U., G.K., and R.A.-A.; visualisation, S.T.; supervision, N.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article and its Supplementary Materials, further inquiries can be directed to the corresponding author/s.

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

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