

Article

Integration of Digital Twin and Circular Economy in the Construction Industry

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Abstract: As a major industry sector, construction is gradually transitioning from the linear economy to the circular economy. Due to various barriers or challenges, the circular economy within construction progresses at a slow pace. Digital technologies can help construction address these barriers or challenges. As a new generation of digital technologies, the digital twin is still seldom used in construction for the circular economy at the current stage. The purpose of this study is to empirically investigate the implementation of the circular economy, as well as the integration of a digital twin and the circular economy, in construction. Based on a review of the relevant literature, this study adopts a combination of expert interviews as a qualitative research method and questionnaire surveys as a quantitative research method. The findings of this study suggest that design and demolition, which are closely linked to each other with regard to circular economy strategies, are more important than other project phases. The digital twin has great potential to improve circular economy practice. It can play some important roles in different project phases throughout the life cycle of a construction project, to achieve the circular economy. Digital twin–circular economy integration makes it effective for construction to overcome circular economy barriers or challenges, reduce waste, and increase salvage value.

Keywords: circular economy; digital twin; construction industry; waste minimization; salvage value



Citation: Meng, X.; Das, S.; Meng, J. Integration of Digital Twin and Circular Economy in the Construction Industry. *Sustainability* **2023**, *15*, 13186. <https://doi.org/10.3390/su151713186>

Academic Editor: Giovanni De Feo

Received: 21 July 2023

Revised: 27 August 2023

Accepted: 29 August 2023

Published: 1 September 2023



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1. Introduction

Traditionally, natural resource utilization always followed a linear approach based on the concept that materials are obtained, utilized, and finally discarded as waste [1]. This “take-make-dispose” approach significantly threatened the sustainability of the natural environment, resulting in natural resource waste and carbon dioxide emissions [2]. As a major industry sector in many countries, construction is responsible for 50% of raw material consumption and 35% of carbon dioxide emissions [3]. To eliminate natural resource waste, minimize carbon dioxide emissions, and ultimately protect the natural environment, there is a call for a paradigm shift from the linear economy to the circular economy in the construction industry [4]. The circular economy achieves its strategic goals through by-product exchange, product reuse, and material recycling, in which products imply building components, units, or systems [5]. For this reason, the paradigm shift is also described as an industrial revolution that transforms construction from the “cradle to grave” model to the “cradle to cradle” model [3].

Although the circular economy is called for, there are various barriers or challenges to achieving circular economy goals in construction. Based on a comprehensive literature review, Charef et al. [6] classified circular economy barriers in construction into six categories: organizational, economical, technical, social, political, and environmental barriers. Wuni [7] described 11 categories of circular economy barriers in construction, including cultural, market, knowledge, financial, management, regulatory, technological, supply chain, stakeholder, technical, and organizational barriers. Osei-Tutu et al. [8] categorized

circular economy barriers in construction into six groups, namely, cultural, social, environmental, economic, technical, and technological barriers. Notably, technological/technical barriers or challenges to the circular economy in construction are commonly identified by various studies. According to Bressanelli et al. [9] and Elghaish et al. [10], emerging technologies, especially digital technologies, have an important role to play in overcoming the technological/technical barriers or challenges to the circular economy in construction. In addition to these technological/technical barriers or challenges, digital technologies also help address other barriers or challenges [11].

Among digital technologies in construction, building information modeling (BIM) is the most frequently reported digital technology in existing studies on the circular economy. For example, Charef and Emmitt [11] explored the use of BIM for overcoming the barriers to the circular economy. Jayasinghe and Waldmann [12] established a BIM-based system as a material and component bank for the circular economy. Xue et al. [13] analyzed BIM for a life cycle assessment to facilitate the circular economy. Sanchez et al. [14] developed BIM-based disassembly models for the reuse of building components. In contrast, some studies paid attention to the integration of BIM and other digital technologies for the circular economy. For example, O'Grady et al. [15] integrated BIM and virtual reality for the circular economy in prefabricated construction. Copeland and Bilec [16] combined BIM and radio frequency identification to support the circular economy through building material banks. Elghaish et al. [17] provided an integrated BIM–blockchain solution to digitalize circular construction supply chains.

The digital twin can be defined as the virtual model that represents a replica of the physical asset, through such technologies as sensors, communication networks, and 3D models, which collects and sends real-time information [18]. Compared to other digital technologies, the digital twin has the potential to better acquire, consolidate, and provide information about the circular economy [19]. For this reason, it is possible for the digital twin to make more contributions to the success of circular economy implementation [20]. Although the digital twin can be used in different phases of a construction project, such as design, construction, operation and maintenance, and demolition, for different purposes [21], the digital twin for the circular economy has rarely been studied in construction. Among the limited number of relevant studies, Chen and Huang [22] proposed a conceptual solution to applying the digital twin for the circular economy in construction. However, few studies to date empirically investigated the digital twin for the circular economy in construction using both qualitative and quantitative research methods. Therefore, there is a lack of clear and deep understanding in this research field.

This study is a new research attempt about using the digital twin for the circular economy in construction, through an empirical investigation using both qualitative and quantitative research methods. It aims to explore the implementation of the circular economy and the integration of the digital twin and the circular economy in construction. It defines the following five research objectives: (1) to investigate the development of circular economy implementation in the construction industry; (2) to demonstrate design and demolition as the two main project phases for circular economy implementation; (3) to establish a link between design and demolition for circular economy implementation; (4) to look into the advancement of digital twin application in the construction industry; (5) to identify the potential of integrating the digital twin and the circular economy; (6) to recognize the role of digital twin application in circular economy implementation. Based on this study, a thorough understanding is provided for the circular economy, the digital twin, and their integration in the construction industry.

2. Circular Economy and Digital Twin

2.1. Circular Economy in Construction

Four key factors enabling the circular economy in construction include (1) education, awareness, and communication; (2) policy and regulation; (3) technology and innovation; and (4) collaboration among stakeholders [1]. According to Tserng et al. [23], the circular

economy in construction follows the 5R principles: (1) Rethink, which targets the maximum efficiency of resource utilization through innovation; (2) Reduce, which targets the minimum usage of resources through production and consumption; (3) Reuse, which targets the maximum usage of a product through relocation or resell; (4) Repair, which targets the maximum lifespan of a product through repair and maintenance; (5) Recycle, which targets the minimum usage of new resources by reprocessing materials. During the whole life cycle of a construction project, the design phase is related to all the 5R principles; the construction phase is related to Rethink, Reduce, Reuse, and Recycle; the operation and maintenance phase is related to Rethink, Reduce, Reuse, and Repair; and the demolition phase is related to Rethink, Reuse, and Recycle [23].

A fundamental task of the circular economy is to reduce waste and increase the salvage value of a built asset, which refers to the value of the built asset at the end of its lifetime during demolition in terms of its reused components and recycled materials, for component reuse and material recycling [10]. The idea of the salvage value is often used in life cycle assessment or life cycle costing [24]. Among existing salvage value studies, Jiang et al. [25] created an economic metric with the salvage value to measure circularity performance in construction, based on life cycle thinking. Akanbi et al. [26] developed a BIM-based life cycle performance system to estimate the salvage value of built assets. According to Cheshire [27], salvageability should be considered during circular design. It enables designers to optimize circular design using components and materials with an inherently high salvage value [10]. In doing so, waste can be minimized while the salvage value can be maximized.

2.2. Digital Twin

BIM was often used for the circular economy in construction, contributing to circular economy implementation. However, BIM is static because it is unable to deal with real-time information [28]. Unlike BIM, the digital twin is good at dealing with real-time and dynamic information. This significant difference explains why there is an increasing call for moving from BIM to digital twin in the construction industry [29]. The following terms often come with digital twin concepts and definitions: (1) virtual representation (i.e., a digital replica of real-world entities); (2) real-world entities (i.e., objects, processes, or physical assets); (3) synchronization (i.e., the connection between the virtual representation and real-world entities); (4) frequency (i.e., the timing of physical-to-virtual synchronization); (5) fidelity (i.e., the degree of precision and accuracy applied to the virtual representation) [30]. Due to the features of the digital twin, such studies as Preut et al. [20] in general and Chen and Huang [22] in construction believed that the digital twin becomes a new generation of digital technologies to support circular economy research and practice.

Many studies showcase digital twin application in construction in different project phases for different purposes. For example, Chen and Whyte [31] developed an innovative approach to predict design change propagation using a digital-twin-driven design structure matrix. Ye et al. [32] proposed a digital-twin-based multi-information intelligent early warning and safety management platform during construction. Xie et al. [33] presented a digital-twin-enabled fault detection and diagnosis process for building systems during operation and maintenance. Züst et al. [34] created a new system using the digital twin for material information integration and material flow management during demolition. Shen et al. [35] established a conceptual framework that integrates BIM and the digital twin to support whole-life-cycle net-zero carbon buildings. Among these construction studies on digital twin application, only a few of them, such as Züst et al. [34], have relevance to circularity. This phenomenon further demonstrates the need for an empirical study on the integration of the digital twin and the circular economy.

3. Research Methods

This study started with a comprehensive review of the literature on circular economy, digital technologies for circular economy, digital twin, and digital twin for circular economy.

The literature reviewed in this study included journal articles, conference papers, books, and industry reports. Most of them were published in the last five years. In this study, journal articles represented the majority of the publications selected for the literature review, which came from various sources, such as Scopus, Web of Science, ScienceDirect, and Google Scholar. The articles were carefully selected from high-impact international journals, such as *Automation in Construction*, *Building and Environment*, *Building Research and Information*, *Buildings*, *Computers in Industry*, *Construction Innovation*, *Energies*, *Engineering*, *Construction and Architectural Management*, *Journal of Building Engineering*, *Journal of Cleaner Production*, *Journal of Information Technology in Construction*, *Renewable and Sustainable Energy Reviews*, *Resources*, *Conservation and Recycling*, *Smart and Sustainable Built Environment*, *Sustainability*, and *Waste Management*. The literature review provided an up-to-date understanding of relevant research topics. It established a solid foundation for the qualitative and quantitative research in this study.

The literature review was followed by semi-structured interviews with six industrial experts in construction to collect qualitative empirical information. These experts had sufficient experience in circular economy and digital twin. The roles of these experts in their organizations included digital construction director, digital twin specialist, senior design manager, and environmental manager. The digital twin specialist interviewee had four years of work experience in digital twin application. The digital construction director interviewee had work experience of 42 years in the construction industry, including work experience in digital construction. The three environmental manager interviewees had five years, seven years, and eight years of work experience in implementing circular economy. The senior design manager interviewee had 20 years of work experience in building design, including work experience in circular design. Each interview lasted at least one hour. The interviews were conducted from June to July 2022. During each interview, 15–17 questions were asked, depending on each interviewee's expertise, which included questions about the current status of circular economy implementation, the current status of digital twin application, the possibility of integrating digital twin and circular economy, the role of digital twin for circular economy, the importance of some project phases over others in terms of circular economy implementation, and so on. Appendix A contains samples of the questions asked during interview. The interviews were recorded and transcribed. The interview transcripts were coded and analyzed using NVivo as a qualitative data analysis tool.

Based on the literature review and qualitative interviews, an online questionnaire survey was conducted from August to September 2022 to collect quantitative empirical information for this study. There were three sections of the questionnaire. The first section was about the role, experience, organization type, and continent (where they are based) of a respondent. The second section asked questions regarding circular economy implementation, digital twin application, and the integration of digital twin and circular economy. The third section examined the importance of design and demolition as two main project phases and the link between design and demolition for circular economy implementation. The questionnaire was distributed to approximately 220 experienced construction practitioners around the world through social networking platforms, such as LinkedIn professional groups. As a result of the questionnaire survey, 107 valid responses were returned, representing a response rate of 48.6%. The collection of questionnaire survey responses worldwide made it possible to compare circular economy, digital twin, and their integration between different parts of the world. The questionnaire survey responses were analyzed using SPSS as a quantitative data analysis tool. Qualitative and quantitative research methods supported each other in this study, providing strong evidence for the research topic.

4. Analysis Results

4.1. Qualitative Data Analysis Results

The circular economy in the construction industry is still at its early stage. This was a consensus of the interviewees in this study. According to some interviewees who had global work experience, the circular economy in construction varies greatly around the world. North European countries provide standard practice and, therefore, set up a good example for the circular economy in construction. In addition to the imbalance of the circular economy in different parts of the world, the interviewees believed that there is an imbalance of the circular economy among construction firms of different sizes. In other words, the circular economy today is mainly limited to large-sized construction firms. Compared to small-sized construction firms, large-sized construction firms have better awareness of the circular economy. Moreover, they have more resources and skills to implement the circular economy in their business models. In contrast, small-sized construction firms do not actively implement the circular economy because they cannot identify the benefits from adopting circular economy strategies. They also have fewer capabilities to implement the circular economy. Regardless of the imbalanced development, all the interviewees had confidence in the transition from the linear economy to the circular economy. This is because the circular economy represents the future of the construction industry.

According to the interviewees, the circular economy should be implemented throughout the whole life cycle of a construction project. However, different project phases may not be equally important for the circular economy. The interviewees believed that design and demolition are more important for the circular economy than other project phases. This is because, as an early phase, design plays a decisive role in the whole project life cycle, just as an interviewee said: “getting your design right means getting 90% of your project right”. Traditional design misses the thinking of circularity. In contrast to traditional design, circular design takes circular principles, such as selection of recyclable materials, into account. This explains why an interviewee thought that design is the only phase where fundamental decisions are made for the circular economy and “anything else is a Band-Aid effect”. As an end-of-life phase, demolition is also crucial for circular economy implementation. Traditional demolition meant “using giant machines to tear everything down” and “disposing components and materials as waste”. Unlike traditional demolition, deconstruction provides an innovative demolition approach, through which “reusable components and recyclable materials achieve circularity”. In addition to the emphasis on design and demolition as the two main project phases for the circular economy, the interviewees identified an inherent link between design and demolition. For example, if recyclable materials are selected during circular design, it is possible to recycle materials during deconstruction. Evidently, the interviewees supported “design for deconstruction” as a key concept of the circular economy.

Although digital twin application is still in its infancy in the construction industry, a mutual understanding of the interviewees in this study is that construction has started its journey from BIM to the digital twin, which represents a new generation of digital technologies. An interviewee described the digital twin as “going beyond BIM to create a live virtual model that responds and behaves like its real-world counterpart”. Some interviewees provided real examples to illustrate the development of digital twin models and the utilization of digital twin systems in their organizations. In this study, the interviewees believed that the digital twin can be used in different phases or throughout the life cycle of a construction project. They also believed that all the parties of a construction project, such as the client, architect, engineer, contractor, project manager, consultant, and facility manager, can benefit from the use of the digital twin in practice. Undoubtedly, all the interviewees supported the integration of the digital twin and the circular economy in the construction industry.

Compared to the utilization of the digital twin for other purposes in construction, the digital twin for the circular economy has been reported much less often by existing studies. However, according to the interviewees in this study, the digital twin has great potential to

improve the circular economy in construction. The interviewees believed that digital twin systems have important roles to play in different project phases for the circular economy. For example, digital-twin-based design simulations can make design for deconstruction more effective and enable access to critical information about the attributes and life cycle performance of different materials for better material selection. Digital twin systems and their sensor networks contribute to recording material usages, tracking material changes, managing material flows, and improving material passports from design to construction and then operation and maintenance to demolition. In the demolition phase, digital twin systems help segregate reusable components and recyclable materials, analyze the quality of salvaged components and materials, perform resource recovery assessment, etc. In addition, the interviewees also identified some other roles of the digital twin in the circular economy for different project phases, such as predictive maintenance during operation and maintenance. Based on the interview results, a word cloud of digital twin for circular economy was constructed (Figure 1).



Figure 1. Word cloud of digital twin for circular economy.

4.2. Quantitative Data Analysis Results

Among the 107 questionnaire survey respondents, there were 11 architects, 8 engineers, 26 project managers, 3 contractor representatives, 8 facility managers, 23 sustainability managers, and 28 specialist consultants. The continental distribution showed no (0%) responses from South America, 1 (0.9%) response from Africa, 2 (1.9%) responses from Oceania, 23 (21.5%) responses from Asia, 24 (22.4%) responses from North America, and 57 (53.3%) responses from Europe. With regard to the question about the circular economy implementation in a respondent's organization, 55 (51.4%) respondents answered "Yes", 38 (35.5%) respondents answered "No", and 14 (13.1%) respondents chose "In the process of adoption". This finding is inspiring because more than 50% of the respondents' organizations have adopted circular economy strategies. Despite this, circular economy implementation is still not widely accepted or ubiquitous in the construction industry. As

for the question about digital twin application in a respondent's organization, 47 (43.9%) respondents answered "Yes", 35 (32.7%) respondents answered "No", and 25 (23.4%) respondents chose "In the process of adoption". This finding suggests that digital twin technologies are applied in less than 50% of the respondents' organizations. Compared to circular economy implementation, digital twin application is even more uncommon in construction.

As shown in Table 1, 87 (81.3%) out of the 107 respondents recognized the importance of considering the circular economy early during design to reduce waste, including 44 (41.1%) respondents who agreed and 43 (40.2%) respondents who strongly agreed. Among the 107 respondents, 92 (86.0%) respondents confirmed the contribution of successfully implementing the circular economy during demolition to increase salvage value, including 42 (39.3%) respondents who agreed and 50 (46.7%) respondents who strongly agreed. Evidently, most questionnaire survey respondents in this study considered design and demolition as the two main project phases that contribute to reducing waste and increasing salvage value. Compared to other project phases, they are more important. On the other hand, 82 (76.6%) respondents determined the close link between design and demolition for circular economy implementation (see Table 1), including 33 (30.8%) respondents who agreed and 49 (45.8%) respondents who strongly agreed. As a result, quantitative empirical evidence is provided in this study for the concept of "design for deconstruction".

Table 1. Circular economy, digital twin, and their integration.

No	Indicator	SD	D	N	A	SA	Total
1	Early consideration of the circular economy during design to reduce waste	-	2 (1.9%)	18 (16.8%)	44 (41.1%)	43 (40.2%)	107 (100%)
2	Successful implementation of the circular economy during demolition to increase salvage value	-	-	15 (14.0%)	42 (39.3%)	50 (46.7%)	107 (100%)
3	Close link between design and demolition to facilitate circular economy implementation	-	7 (6.5%)	18 (16.8%)	33 (30.8%)	49 (45.8%)	107 (100%)
4	Integration of the digital twin and the circular economy to overcome circular economy barriers	-	-	24 (22.4%)	39 (36.4%)	44 (41.1%)	107 (100%)
5	Early integration of the digital twin and the circular economy since design	-	6 (5.6%)	25 (23.4%)	31 (29.0%)	45 (42.1%)	107 (100%)

SD: strongly disagree; D: disagree; N: neutral; A: agree; SA: strongly agree; -: no response.

According to Table 1, 83 (77.5%) out of the 107 respondents supported the integration of the digital twin and the circular economy, including 39 (36.4%) respondents who agreed and 44 (41.1%) respondents who strongly agreed. They believed that digital twin–circular economy integration can help construction overcome the barriers or challenges to the circular economy. No respondents disagreed with the integration of the digital twin and the circular economy. Among the 107 respondents, 76 (71.1%) respondents considered digital twin–circular economy integration since design as a key for circular economy implementation, including 31 (29.0%) respondents who agreed and 45 (42.1%) respondents who strongly agreed. It was their view that the early integration of the digital twin and the circular economy since design has a significant impact on the success of later project phases in the context of the digital twin for the circular economy. Apart from the digital twin itself, some respondents identified the possibility of using the digital twin along with some other digital technologies to better implement circular economy, among which cloud computing was identified by 6 (5.6%) respondents, big data was identified by 12 (11.2%) respondents, BIM was identified by 15 (14.0%) respondents, artificial intelligence was identified by 31

(29.0%) respondents, and multiple other digital technologies were identified by 43 (40.2%) respondents.

The circular economy, the digital twin, and their integration are compared in Table 2 regarding the responses from Asia, Europe, and North America. As previously mentioned, among the 107 questionnaire survey responses, no responses came from South America, only one response came from Africa, and only two responses came from Oceania. For this reason, South America, Africa, and Oceania are not included in Table 2 when making a comparative analysis due to a lack of statistical sense. Except for “Integration of digital twin and circular economy to overcome circular economy barriers”, the European responses are more positive in all aspects than the Asian and North American responses. Regarding “Integration of digital twin and circular economy to overcome circular economy barriers”, the Asian, European, and North American responses are nearly the same. Similarly, there are no significant differences among the Asian, European, and North American responses for “Successful implementation of circular economy during demolition to increase salvage value” and “Close link between design and demolition to facilitate circular economy implementation”. In contrast, it is apparent that “Early consideration of circular economy during design to reduce waste” and “Early integration of digital twin and circular economy since design” are significantly different among the Asian, European and North American responses. This means that, by comparison, the European responses pay more attention to “Early consideration of circular economy during design” and “Early integration of digital twin and circular economy since design”.

Table 2. Comparison of circular economy, digital twin, and their integration among continents.

No	Indicator	Continent Base				ANOVA	
		Asia n = 23	Europe n = 57	North America n = 24	Total n = 104	F	Sig
1	Early consideration of the circular economy during design to reduce waste	3.57	4.58	3.96	4.21	21.379	<0.001
2	Successful implementation of the circular economy during demolition to increase salvage value	4.22	4.42	4.21	4.33	1.091	0.340
3	Close link between design and demolition to facilitate circular economy implementation	4.00	4.30	3.92	4.14	1.768	0.176
4	Integration of the digital twin and the circular economy to overcome circular economy barriers	4.17	4.18	4.21	4.18	0.017	0.983
5	Early integration of the digital twin and the circular economy since design	3.57	4.42	3.75	4.08	10.185	<0.001

5. Discussion

Previous studies, such as those by Hossain et al. [4], Oluleye et al. [36], and Husgafvel and Sakaguchi [37], point out that the circular economy in the construction industry is still at its early stage. For such a viewpoint, this study is consistent with previous studies. In addition to early-stage development, imbalanced development is also identified in this study for the circular economy in construction. According to the qualitative analysis of the interviews, two scenarios of imbalanced development exist: one is the imbalance of circular economy implementation in different parts of the world, and the other is the imbalance of circular economy implementation in construction firms of different sizes. The quantitative analysis of the questionnaire survey responses further demonstrates the imbalance of circular economy understanding and practice in different parts of the world. Despite early-stage development and imbalanced development, both the qualitative research and

quantitative research in this study share a common outlook: significant changes for the circular economy will gradually take place in construction. This is because the circular economy represents the future of the construction industry.

Various barriers or challenges to the circular economy in construction were identified by previous studies, such as those by Charef et al. [6], Wuni [7], and Osei-Tutu et al. [8]. This explains why the circular economy in construction is progressing at a slow pace. Although construction has started its journey toward digital twin technologies, few studies to date investigated the digital twin for the circular economy in construction. According to all the interviewees and 83% of the questionnaire survey respondents in this study, the integration of the digital twin and the circular economy contributes to overcoming circular economy barriers or challenges in construction. Based on the qualitative analysis of the interviewees, the digital twin can be considered as a new generation of digital technologies to accelerate the changes for the circular economy in construction. Meanwhile, the digital twin has various roles to play in different project phases for the circular economy. The quantitative analysis of the questionnaire survey responses further demonstrates the possibility to combine the digital twin and some other digital technologies, such as BIM, cloud computing, big data, and artificial intelligence, to better implement the circular economy in construction.

As mentioned above, a fundamental task of the circular economy is to reduce waste and increase the salvage value of a built asset. Yuan et al. [38] assessed the effects of management strategies for reducing construction and demolition waste. Salgn et al. [39] developed a BIM-based site management approach for construction waste reduction. Jiang et al. [25] created an economic metric with the salvage value to measure circularity performance in construction, based on life cycle thinking. Akanbi et al. [26] developed a BIM-based life cycle performance system to estimate the salvage value of built assets. This study goes an important step further, highlighting the integration of the digital twin and the circular economy or the integration of the digital twin along with some other digital technologies and the circular economy. Such an integration provides a revolutionary path for waste minimization and salvage value maximization.

It is appropriate to look at the circular economy in construction from the project life cycle perspective [40]. Many studies believe that the circular economy should start from design, as an early phase of a construction project. For example, Charef et al. [41] revealed that a large proportion of waste in construction projects originates from design. Benachio et al. [42] encouraged introducing the circular economy early in design decision making. Guerra et al. [43] realized that circular economy strategies and tools should be adopted for design optimization, as design determines the overall performance of a project. This study qualitatively and quantitatively provides empirical evidence to support life cycle thinking and the early involvement of the circular economy in design. More importantly, this study identifies the key roles that the digital twin can play in different project phases for the circular economy. It also suggests integrating the digital twin and the circular economy from design to construction and then operation and maintenance to demolition. As a result, the digital twin and the circular economy are integrated throughout the project life cycle so that the benefits of their integration can be maximized.

This study has both theoretical and practical implications. From the theoretical perspective, it provides a thorough understanding of the circular economy, the digital twin, and their integration in the construction industry. In particular, such an understanding contributes to the knowledge development of digital twin–circular economy integration. In addition to the theoretical implications, this study also has practical implications. It provides the construction industry with an innovative solution to circular economy barriers/challenges using the digital twin. The information and experience provided in this study contribute to industrial development in terms of both the circular economy and the digital twin.

6. Conclusions

This study encourages life cycle thinking for the circular economy in construction. It is found in this study that design as an early and decisive phase and demolition as a late and end-of-life phase are more important for circular economy implementation, compared to other project phases. Meanwhile, design and demolition are closely linked with each other, for the circular economy to achieve success. The findings of this study support the concept of “design for deconstruction”. In doing so, waste can be reduced while the salvage value can be increased. This study discovers that, currently, circular economy implementation is still in its early stage. Various barriers or challenges to the circular economy exist in construction, and, therefore, the circular economy in construction progresses at a slow pace. For this reason, it is necessary for construction to find new and effective ways of implementing the circular economy. Current digital technologies, such as BIM, prove useful for circular economy implementation.

This study reveals that construction is moving from BIM to the digital twin as a new generation of digital technologies. Compared to the digital twin for other purposes in construction, the digital twin for the circular economy is still very limited today. Despite that, the digital twin has a great potential to overcome circular economy barriers or challenges in construction. Based on qualitative and quantitative empirical evidence, this study advocates for integrating the digital twin and the circular economy in construction. It is found in this study that the digital twin has various roles to play in the different phases of a construction project for the circular economy. It is also found that the digital twin can be used to implement the circular economy throughout the whole project life cycle. On one hand, digital twin–circular economy integration helps construction overcome barriers or challenges to the circular economy. On the other hand, such an integration extends the sphere of digital twin application in the construction industry.

Although this study has both academic and industrial implications, it has limitations. First of all, due to the time limit, only six industrial experts were interviewed in this study to collect qualitative information. Future research is recommended to conduct more expert interviews so that it becomes possible to collect more in-depth information about the circular economy, the digital twin, and digital twin–circular economy integration for qualitative data analysis. Secondly, among the 107 questionnaire survey responses in this study, there were no response from South America, only one response from Africa, and only two responses from Oceania. A recommendation for future research is to collect more responses from these three continents, based on which a better international comparison can be made for the circular economy, the digital twin, and digital twin–circular economy integration through quantitative data analysis. The qualitative analysis of interviews enables this study to briefly identify the roles of the digital twin in different project phases for the circular economy. Future research may perform a specific investigation to identify the roles of the digital twin for the circular economy in a systematic way. As a result, it becomes possible for academic researchers and industrial practitioners to have a better understanding of digital twin application for circular economy implementation phase by phase. This study adopts a combination of expert interviews as a qualitative research method and questionnaire surveys as a quantitative research method based on a literature review. Case studies can be used as a research method in future research to provide real-world examples for digital twin–circular economy integration through specific cases.

Author Contributions: Coneptualization, X.M. and S.D.; methodology, X.M.; software, S.D.; validation, X.M., S.D. and J.M.; formal analysis, X.M.; investigation, S.D.; resources, S.D.; data curation, S.D.; writing—original draft preparation, X.M.; writing—review and editing, J.M.; visualization, X.M.; supervision, X.M.; project administration, S.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

Appendix A

Sample Questionnaire

Part 1

1.1 Please select your role.

- ☐ Architect
- ☐ Engineer
- ☐ Project manager
- ☐ Contractor representative
- ☐ Facility manager
- ☐ Sustainability manager
- ☐ Specialist consultant
- ☐ Other

1.2 Please select your relevant experience in the construction industry.

- ☐ 0–1 year
- ☐ 2–4 years
- ☐ 5–10 years
- ☐ 10–20 years
- ☐ >20 years

1.3 On which continent is your company based?

- ☐ Africa
- ☐ Asia
- ☐ Europe
- ☐ North America
- ☐ Oceania
- ☐ South America
- ☐ Others

1.4 What types of construction projects does your company generally handle?

- ☐ Residential
- ☐ Educational
- ☐ Healthcare
- ☐ Commercial
- ☐ Industrial
- ☐ Infrastructure
- ☐ Others

Part 2

2.1 Has your company previously used or is it currently using the circular economy approach in any of its projects?

- ☐ Yes
- ☐ No
- ☐ In the process of adoption

2.2 Does your company adopt the digital twin or does it have any plans for the adoption of the digital twin?

- ☐ Yes
- ☐ No
- ☐ In the process of adoption

2.3 Do you agree with the integration of the digital twin and the circular economy to overcome circular economy barriers?

- ☐ Strongly disagree
- ☐ Disagree

- ☐ Neutral
 - ☐ Agree
 - ☐ Strongly agree
- 2.4 Do you agree with the early integration of the digital twin and the circular economy since design?
- ☐ Strongly disagree
 - ☐ Disagree
 - ☐ Neutral
 - ☐ Agree
 - ☐ Strongly agree
- 2.5 What are the suitable digital technologies that can be used along with the digital twin to better implement the circular economy?
- ☐ Artificial intelligence
 - ☐ Building information modeling
 - ☐ Big data
 - ☐ Cloud computing
 - ☐ Others

Part 3

- 3.1 How important is the early consideration of the circular economy during design to reduce waste?
- ☐ Very unimportant
 - ☐ Unimportant
 - ☐ Neither unimportant nor important
 - ☐ Important
 - ☐ Very important
- 3.2 How important is the demolition phase for increasing the salvage value?
- ☐ Very unimportant
 - ☐ Unimportant
 - ☐ Neither unimportant nor important
 - ☐ Important
 - ☐ Very important
- 3.3 Do you agree that there is a close link between design and demolition for circular economy implementation?
- ☐ Strongly disagree
 - ☐ Disagree
 - ☐ Neutral
 - ☐ Agree
 - ☐ Strongly agree

References

- Arup. *The Circular Economy in the Built Environment*; Arup: London, UK, 2016; pp. 1–10.
- Lieder, M.; Rashid, A. Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *J. Clean. Prod.* **2016**, *115*, 36–51. [\[CrossRef\]](#)
- Mrad, C.; Ribeiro, L.F. A review of Europe's circular economy in the building sector. *Sustainability* **2022**, *14*, 14211. [\[CrossRef\]](#)
- Hossain, M.U.; Ng, S.T.; Antwi-Afari, P.; Amor, B. Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109948. [\[CrossRef\]](#)
- Wuni, I.Y. Drivers of circular economy adoption in the construction industry: A systematic review and conceptual model. *Build. Res. Inf.* **2023**, *51*, 816–833. [\[CrossRef\]](#)
- Charef, R.; Morel, J.-C.; Rakhshan, K. Barriers to implementing the circular economy in the construction industry: A critical review. *Sustainability* **2021**, *13*, 12989. [\[CrossRef\]](#)
- Wuni, I.Y. Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map. *Build. Environ.* **2022**, *223*, 109453. [\[CrossRef\]](#)

8. Osei-Tutu, S.; Ayarkwa, J.; Osei-Asibey, D.; Nani, G.; Afful, A.E. Barriers impeding circular economy (CE) uptake in the construction industry. *Smart Sustain. Built Environ.* **2023**, *12*, 892–918. [\[CrossRef\]](#)
9. Bressanelli, G.; Adrodegari, F.; Perona, M.; Saccani, N. The role of digital technologies to overcome circular economy challenges in PSS business models: An exploratory case study. *Procedia CIRP* **2018**, *73*, 216–221. [\[CrossRef\]](#)
10. Elghaish, F.; Matarneh, S.T.; Edwards, D.J.; Rahimian, F.P.; El-Gohary, H.; Ejohwomu, O. Applications of Industry 4.0 digital technologies towards a construction circular economy: Gap analysis and conceptual framework. *Constr. Innov.* **2022**, *22*, 647–670.
11. Charef, R.; Emmitt, S. Uses of building information modeling for overcoming barriers to a circular economy. *J. Clean. Prod.* **2021**, *285*, 124854. [\[CrossRef\]](#)
12. Jayasinghe, L.B.; Waldmann, D. Development of a BIM-based web tool as a material and component bank for a sustainable construction industry. *Sustainability* **2020**, *12*, 1766. [\[CrossRef\]](#)
13. Xue, K.; Hossain, M.U.; Liu, M.; Ma, M.; Zhang, Y.; Hu, M.; Chen, X.Y.; Cao, G. BIM integrated LCA for promoting circular economy towards sustainable construction: An analytical review. *Sustainability* **2021**, *13*, 1310. [\[CrossRef\]](#)
14. Sanchez, B.; Rausch, C.; Haas, C.; Hartmann, T. A framework for BIM-based disassembly models to support reuse of building components. *Resour. Conserv. Recycl.* **2021**, *175*, 105825. [\[CrossRef\]](#)
15. O'Grady, T.M.; Brajkovich, N.; Minunno, R.; Chong, H.-Y.; Morrison, G.M. Circular economy and virtual reality in advanced BIM-based prefabricated construction. *Energies* **2021**, *14*, 4065. [\[CrossRef\]](#)
16. Copeland, S.; Bilec, M. Buildings as material banks using RFID and building information modeling in a circular economy. *Procedia CIRP* **2020**, *90*, 143–147. [\[CrossRef\]](#)
17. Elghaish, F.; Hosseini, M.R.; Kocaturk, T.; Arashpour, M.; Ledari, M.B. Digitalized circular construction supply chain: An integrated BIM-Blockchain solution. *Autom. Constr.* **2023**, *148*, 104746. [\[CrossRef\]](#)
18. Madubuike, O.C.; Anumba, C.J.; Khallaf, R. A review of digital twin applications in construction. *J. Inf. Technol. Constr.* **2022**, *27*, 145–172. [\[CrossRef\]](#)
19. Bressanelli, G.; Adrodegari, F.; Pigosso, D.C.A.; Parida, V. Circular economy in the digital age. *Sustainability* **2022**, *14*, 5565. [\[CrossRef\]](#)
20. Preut, A.; Kopka, J.-P.; Clausen, U. Digital twins for the circular economy. *Sustainability* **2021**, *13*, 10467. [\[CrossRef\]](#)
21. Opoku, D.-G.J.; Perera, S.; Osei-Kyei, R.; Rashidi, M. Digital twin application in the construction industry: A literature review. *J. Build. Eng.* **2021**, *40*, 102726. [\[CrossRef\]](#)
22. Chen, Z.; Huang, L. Digital twin in circular economy: Remanufacturing in construction. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *588*, 032014. [\[CrossRef\]](#)
23. Tserng, H.-P.; Chou, C.-M.; Chang, Y.T. The key strategies to implement circular economy in building projects: A case study of Taiwan. *Sustainability* **2021**, *13*, 754. [\[CrossRef\]](#)
24. Joensuu, T.; Edelman, H.; Saari, A. Circular economy practices in the built environment. *J. Clean. Prod.* **2020**, *276*, 124215. [\[CrossRef\]](#)
25. Jiang, L.; Bhochhibhoya, S.; Slot, N.; de Graaf, R. Measuring product-level circularity performance: An economic value-based metric with the indicator of residual value. *Resour. Conserv. Recycl.* **2022**, *186*, 106541. [\[CrossRef\]](#)
26. Akanbia, L.A.; Oyedele, L.O.; Akinade, O.O.; Ajayia, A.O.; Delgado, M.D.; Bilala, M.; Bellob, S.A. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resour. Conserv. Recycl.* **2018**, *129*, 175–186. [\[CrossRef\]](#)
27. Cheshire, D. *Building Revolutions: Applying the Circular Economy to the Built Environment*; RIBA Publishing: Newcastle, UK, 2016; pp. 65–79.
28. Tanga, S.; Sheldena, D.R.; Eastmana, C.M.; Pishdad-Bozorgib, P.; Gao, X. A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Autom. Constr.* **2019**, *101*, 127–139. [\[CrossRef\]](#)
29. Deng, M.; Menassa, C.C.; Kamat, V.R. From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *J. Inf. Technol. Constr.* **2021**, *26*, 58–83. [\[CrossRef\]](#)
30. RICS. *Digital Twins from Design to Handover of Construction Assets*; RICS: London, UK, 2022; pp. 7–12.
31. Chen, L.; Whyte, J. Understanding design change propagation in complex engineering systems using a digital twin and design structure matrix. *Eng. Constr. Archit. Manag.* **2022**, *29*, 2950–2975. [\[CrossRef\]](#)
32. Ye, Z.; Ye, Y.; Zhang, C.; Zhang, Z.; Li, W.; Wang, X.; Wang, L.; Wang, L. A digital twin approach for tunnel construction safety early warning and management. *Comput. Ind.* **2023**, *144*, 103783. [\[CrossRef\]](#)
33. Xie, X.; Merino, J.; Moretti, N.; Pauwels, P.; Chang, J.Y.; Parlikad, A. Digital twin enabled fault detection and diagnosis process for building HVAC systems. *Autom. Constr.* **2023**, *146*, 104695. [\[CrossRef\]](#)
34. Züst, S.; Züst, R.; Züst, V.; West, S.; Stoll, O.; Minonne, C. A graph based Monte Carlo simulation supporting a digital twin for the curatorial management of excavation and demolition material flows. *J. Clean. Prod.* **2021**, *310*, 127453. [\[CrossRef\]](#)
35. Shen, K.; Ding, L.; Wang, C.C. Development of a framework to support whole-life-cycle net-zero-carbon buildings through integration of building information modelling and digital twins. *Buildings* **2022**, *12*, 1747. [\[CrossRef\]](#)
36. Oluleye, B.I.; Chan, D.W.M.; Saka, A.B.; Olawumi, T.O. Circular economy research on building construction and demolition waste: A review of current trends and future research directions. *J. Clean. Prod.* **2022**, *357*, 131927. [\[CrossRef\]](#)
37. Husgafvel, R.; Sakaguchi, D. Circular economy development in the construction sector in Japan. *World* **2022**, *3*, 1–26. [\[CrossRef\]](#)
38. Yuan, H.; Chini, A.R.; Lu, Y.; Shen, L. A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. *Waste Manag.* **2012**, *32*, 521–531. [\[CrossRef\]](#) [\[PubMed\]](#)

39. Salgn, B.; Akgün, A.; Cosgun, N.; Agyekum, K. Construction waste reduction through BIM-based site management approach. *Int. J. Eng. Technol.* **2017**, *3*, 135–142. [[CrossRef](#)]
40. Sharma, N.; Kalbar, P.P.; Salman, M. Global review of circular economy and life cycle thinking in building demolition waste management: A way ahead for India. *Build. Environ.* **2022**, *222*, 109413. [[CrossRef](#)]
41. Charef, R.; Lu, W.; Hall, D. The transition to the circular economy of the construction industry: Insights into sustainable approaches to improve the understanding. *J. Clean. Prod.* **2022**, *364*, 132421. [[CrossRef](#)]
42. Benachio, G.L.F.; Freitas, M.d.C.D.; Tavares, S.F. Circular economy in the construction industry: A systematic literature review. *J. Clean. Prod.* **2020**, *260*, 121046. [[CrossRef](#)]
43. Guerra, B.C.; Shahi, S.; Mollaei, A.; Skaf, N.; Weber, O.; Leite, F.; Haas, C. Circular economy applications in the construction industry: A global scan of trends and opportunities. *J. Clean. Prod.* **2021**, *324*, 129125. [[CrossRef](#)]

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