Developing a Methodological Framework for Adopting Digitalization for Deconstruction Planning

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Abstract. Wastes generated from construction and demolition (C&D) activities account for a major proportion of urban solid wastes. The large amount of C&D waste generated are still being largely landfilled or downcycled worldwide. Aging built assets without proper C&D planning is a major cause of wastes not being efficiently diverted for circular use. How waste sorting could be properly planned in the early stages, not only for new construction, but also deconstruction projects is critical to minimizing C&D wastes. As there is a large amount of aging assets without digital files or even no drawings, developing a digital-driven approach to effectively estimate and categorize C&D wastes would be essential for, not just early-stage deconstruction planning, but also the development of a circular economy on C&D wastes. This study is first based on a thorough literature review of existing studies of applications of digital technologies to C&D waste diversion (WD). Limitations of existing studies are evaluated, such as the lack of digital twin approach for deconstruction. Then a methodological framework is established aiming to adopt digitalization for C&D WD, specifically for existing facilities under deconstruction planning. Based on the current work, future study would ap-ply the methodological framework with real-world case studies to validate and test its effectiveness with initiated prototypes. Longer-term work can ex-tend from the current framework to Internet-of-Things and Artificial Intelligence.

Keywords: digitalization; building information modeling; construction waste management; deconstruction; circular economy.

1 Introduction

The rapid urbanization process worldwide especially in developing economies has caused global social and environmental issues, such as overwhelming urban solid wastes occupying limited land spaces, depleting natural resources, and increased carbon emissions. Circular economy (CE), as the concept of addressing circular use of resources and materials, is being integrated to the research and practice of construction and demolition (C&D) waste diversion (WD). C&D wastes accounts for 25% to

30% of all wastes generated in Europe and consists of various materials such as concrete, wood, glass, etc. [1]. CE principles urge construction and built environment professionals to consider the end-of-life (EoL) use of building materials or components. Existing studies [2] focusing on C&D WD have targeted new construction or the early design for WD. Considering EoL C&D WD in the early project stages reflects the life cycle approach, which highlights the cradle-to-grave thinking. The CE principles address the circularity of building materials or components not only at different project stages but also in different life cycles. The concept of material passport is hence applied in describing the dynamic flow of materials crossing stages and cycles. Timely captured information about existing materials/components (M/C) to be discarded is deemed important for a wide community or stakeholder groups [3] in planning for demolition or deconstruction. Compared to demolition, deconstruction is considered a more effective manner to reduce C&D debris [4]. Compared to demolition, deconstruction could incur higher cost depending on multiple factors such as labor costs of sorting wastes, resale values of deconstructed components, tipping fee to landfill, etc [4]. Design for deconstruction (DfD) is emphasized as a critical way to unlock the benefits of CE [5].

Adopting the emerging digital technologies or platforms, such as Building Information Modeling (BIM) for C&D WD, is undergoing continuous progress in terms of the availability of digital technologies and the functionalities in C&D WD. The technological innovation outside of construction industry is driving construction and built environment towards digitalization. Digitalization-driven C&D WD and deconstruction work is reaching more potentials, for example, from early stage waste generation estimate [6] to reconstructing digital models for deconstruction management [7]. Deconstruction, as a more CE-prone approach differing from the conventional demolition for treating EoL built facilities, could be boosted along with wider adoption of digital technologies in CE implementation. This study aims to achieve two objectives related to digitalization for deconstruction planning, namely: 1) to provide an overview of existing research and development of adopting digital technologies or platforms to assist C&D WD and deconstruction planning; and 2) to propose a methodological framework by addressing limitations and integrating digitalization into CE principles. The current study will lead to more future research and practice for enhancing the circularity of EoL building materials especially for deconstruction.

2 Literature Review

2.1 Digitalization for Circular Economy

The majority of studies integrating digital technologies and CE have been published since 2014 [8]. Digital technologies, with connectivity through the Internet of Things (IoT) and the creation of intelligent assets representing the key features of Industrial Revolution 4, can become the enabler of CE [9]. Numerous studies have viewed digitalization as the driver for CE. For example, Bressanelli et al. [10] mentioned IoT, Big Data and Analytics to overcome the challenges in implementing CE in the company level. Specifically, four digitally-enabled functionalities were proposed, named:

1) monitoring users' activities; 2) preventive and predictive maintenance or the optimization of the usage phase; 3) digital upgrade; and 4) estimation of products and components residual life [10]. The estimation of material residual properties apply across industries, including construction materials or components at EoL. Despite of the challenges of CE practices, digitalization is also viewed with promising opportunities of driving CE business model by closing the loop of material flow, saving resources, and reducing costs through accurate data and virtualization [11]. Digitalization also needs the networking and collaboration among stakeholders [11].

Applying digitalization in CE also needs the coordination of different layers or processes including data collection, data integration, and data analysis [8]. At the data collection stage, digital technologies such as Radio Frequency Identification (RFID) could be applied in identifying and tracking material flows and in providing products' life cycle to all networked stakeholders [8,12]. IoT, achieved through sensors and actuators connected by networks, is also recognized of its importance to monitor connected objects [13] in the CE context. Data integration involves heterogeneous data sources across material or product life cycles [8,14]. The large dataset collected and integrated from earlier steps can then be analyzed through Big Data analytics and machine learning approaches [15].

2.2 Digital-driven Construction & Demolition Waste Management

CE is recommended to be applied as an emergent approach and new business model in C&D waste management (WM) [16]. Digital technologies in construction (e.g., BIM) has demonstrated its power in managing C&D WM. Table 1 summarizes several existing studies in adopting different digital technologies for C&D WM. For example, Guerra et al. [6] embedded C&D waste estimate algorithms into BIM for automatically quantifying C&D wastes such as concrete structure and drywall. The work [6] demonstrated how different digital methods could be adopted to save manual effort in estimating different categories of C&D wastes especially from the early project stages.

Table 1. Summary of existing studies adopting digital technologies for C&D WM

Study	Digital technologies adopted	Major focus in C&D WM	Major contribution or findings
Liu et al.[17]	BIM	Effective waste minimization evaluation in design stages, e.g., the virtual waste evaluations of framework to enable further computer program as a percentage of C&D waste generation based on past project data	The study served as a first attempt to develop a design decision-making framework for improving construction waste minimization performance through BIM in design stages.
Paz and Lafayette [18]	Coding of decision support system	Acquiring existing data of C&D waste generation to study its relation to other fac-	A computerized tool (software) was initiated to facilitate the analysis of strategies for WM on construction

		tors (e.g., construction area, number of floors, etc.)	sites through the use of indicators of C&D waste generation.
Won and Cheng [19]	BIM	Design review, 3D coordination, quantity take-off, phase planning, site utilization planning, construction system design, digital fabrication, and 3D control and planning	The study identified and evaluated in-depth of potentials of BIM to enhance C&D WM and minimization. In a process-based approach, reductions in C&D wastes were recommended at the design phase. Insufficient studies had focused on BIM in the demolition phase.
Lu et al. [20]	BIM	Computational BIM algorithms for manipulating the information to facilitate decision-making for C&D WM, e.g., waste generation estimate associated with different design options	A prototypical framework of a computational BIM for C&D WM was delineated, highlighting the two key prerequisites, namely information readiness (e.g., historical data) and computational algorithms.
Madi and Srour	Geographic Information System (GIS)	Automatic siting of suitable land space for C&D waste recycling	A framework incorporating GIS was developed to identify suitable land for C&D waste recycling by accounting for various attributes such as land topology, and transportation costs, etc.
Lu [21]	Big data analytics	Identifying illegal C&D waste dumping	The big data analytics from publicly available data was performed to uncover patterns of illegal behaviors that were linked to illegal waste dumping.
Zou et al.[22]	Data analytics and sensor for monitoring following the concept of IoT	Monitoring of illegal behaviors in handling C&D wastes, e.g., illegal disposal	A new informatization scheme, incorporating centralized and data sharing mechanism, was implemented to manage illegal behaviors of treating C&D wastes.
Kim et al.[23]	BIM	Estimation of demolition wastes (DW) based on waste type and volume using information from BIM starting from the early design stages	The study proposed a BIM-based framework to estimate DW aiming for early project stages using information from material classification system and existing BIM library.
Kunieda et al.[24]	4D motion game engine enabled by simulation algorithms	The impact of demolition processes on waste recovery for studying the relationship between demolition strategy and waste sortability	Simulating & modeling the demolition process associated with the outcomes of C&D waste recovery is a novel by including the time dimension.

Major focuses listed in Table 1 refer to key activities in the research to achieve defined goals of C&D WM, such as reducing waste generation, minimizing transport impacts, maximizing re-use and recycling through improved quality of secondary materials, and optimizing the performance of treatment methods [25]. Several patterns could be uncovered from the review of these existing studies not limited to Table 1, namely: 1) BIM as one of the most widely adopted method to assist C&D WM; 2) recommendations of C&D WM starting from early project stages (e.g., design phases); 3) C&D waste generation estimate as one of the main focuses. Several studies [23,24] have specifically targeted the demolition phase. The study in demolition strategies [24,26] such as sequence, machine, and time planning, provide more practical considerations that handling C&D wastes are not only based on the early stage design and waste estimate, but also deconstruction planning.

2.3 Deconstruction versus Demolition

While demolition generally refers to the complete elimination of all parts of EoL built assets, deconstruction is opposed to demolition which is an undifferentiated process of compressing a building and landfilling all wastes [27]. Insufficient attention has been paid on EoL building components as compared to the research in design and construction stages [27]. Deconstruction, somehow understood as selective demolition, could incur more costs including labor inputs [28]. Despite of the higher costs involved, deconstruction, as the systematic disassembly of buildings to maximize recovered material reuse and recycling, is emerging as an alternative to demolition worldwide [29]. Depending on multiple influence factors such as tipping fee of landfilling, deconstruction can outweigh demolition both economically and environmentally [30].

Demolition could still be considered as the baseline of deconstruction, or the reference strategy in deconstruction. The application of digital technologies (e.g., BIM) has been seen of its functionality in selecting deconstruction strategies. Information such as prices and energy embodiment of materials/components can be stored in BIM allowing comparisons of different deconstruction strategies based on economic and environmental indicators [31]. Akanbi et al. [32] developed disassembly and deconstruction system integrating BIM authoring tools for building element deconstruction analytics, and design for deconstruction (DfD) decision making. The system architecture [32] was also designed to enable deconstruction visualization with virtual reality tools. Akbarieh et al. [33] provided a holistic literature review of BIM for EoL built facilities for minimizing C&D wastes, and identified several main research directions including BIM-based DfD, BIM-based deconstruction, and Materials/Components (M/C) Banks. These directions are not separated from each other, the uncertainties in M/C Banks such as attributes of reusable elements in the "bank" could affect the deconstruction activities as indicated by Akbarieh et al. [33].

3 Research Trends of Digitalization for Deconstruction

A thorough review of these existing studies including those showcased in Table 1 indicates several limitations or trends in bridging digitalization for C&D WM especially deconstruction:

- The digital applications have been limited to BIM, and more connected technologies are yet to be integrated, such as geographic information system, RFID, image analysis, big data, etc., as identified by Li et al. [34]. Interoperability among the software and hardware tools need to be addressed in a systematic approach. The system integrating different digital tools, such as the system architecture described in Akanbi et al. [32] is an example by bridging four different layers for data storage, semantic information, analytics and functional model, as well as the application respectively. The data storage includes information related to M/C specifications, design, and deconstruction/demolition [32]. The historic record of deconstructed buildings would be valuable data source for being "learned" in a machine learning approach for future deconstruction design and other uses. Data saved in certain files under a defined information exchange formats need to be interoperable for transferring among different tools in the system, such as BIM authoring tools, web platform, etc. Inadequate interoperability or connectivity among these digital tools would cause significantly more resources in performing DfD or other CE practices, and lower productivity. The analytics layer is a key part of the system in supporting the main functions of the system, for instance, deconstruction visualization [32]. Finally, the application layer or the end-user layer, typically with a user interface to enable user-system interaction. It should be ideally enable smart decision-making of the optimal deconstruction option through simulation, comparison, and evaluation. The evaluation criteria could be pre-set in the system, for example, cost, carbon, energy, or a weighted and combined evaluation criteria to allow quantifiable comparisons of different deconstruction strategies.
- The connectedness of a variety of digital technologies starting from the system architecture would need to be tested and validated in a socio-technical approach by collecting and analyzing end-users' feedback. The multi-disciplinary stakeholder groups coming from different professions may have their individual perceptions differing from others. There is a need to bridge different stakeholders in order to further standardize the digitalization process and products. The development, trials, validation, and update form a cyclic loop of the digitalization system to implement CE and C&D WM. Collecting and evaluating user feedback for further updates in a developed digital system can be found in other studies [35] of built environment.
- Highlighting early design stages for considering C&D WM is widely found in these existing studies [23] of applying digitalization. Life cycle approach from cradle to grave has been reflected in these existing research. However, the prominent issue of efficiently reconstituting the "bank" of building material coming from the "grave" (i.e., EoL buildings) back to "cradle" (i.e., new construction) has not been fully investigated. Digitalization for C&D could be

more specifically targeting deconstruction following circular principles, such as remanufacturing, reuse, recycle, and recovery, etc.

- These emerging philosophies, such as DfD, are undergoing the rising attention in implementing CE. However, the current DfD may be limited to new construction projects, but not for aging built assets which were mostly without DfD when designed and built. Another issue with existing studies [20] adopting BIM for C&D WM is that BIM might not be available for most existing built facilities. Many aging or existing facilities may be even without design drawings saved, necessitating site survey to gain the information of each built asset to implement deconstruction planning. This would again spark the need of integration of a variety of digital technologies, such as point cloud data to be registered from site surveying to BIM, or scan-to-BIM. As refurbishment or renovation is likely to be the dominating work in the built environment sector compared to new construction, acquiring high-quality raw data for those aging assets without BIM files would be the initial job for deconstruction or reconstruction. To some degree it is true that deconstruction would not exclude refurbishment, repair, or renovation, because deconstruction is a selective demolition for built assets, meaning that part of M/C could remain by being renewed according to its circularity attributes. Further, more stakeholders could be engaged besides demolition-related players, but also those involved in the operation or maintenance stages and in the real estate markets, e.g., housing agents, tenants, and buyers, etc. The designed systematic architecture aforementioned would aim to engage various stakeholders at the maximum level.
- Source and quality of raw data, such as the point cloud registered from site surveying, or as simple as photos for image processing, is the fundamental part for the rest of the digital system in assisting deconstruction planning and decision making. The raw data for information retrieval of attributes regarding circularity, recyclability, or reusability is a key factoring affecting the practicality of the system architecture or prototype. Historical project database would be one of the sources for benchmarking the attributes of individual M/C and for improving the reliability of waste generation estimate. The study of Akanbi et al. [36] serves as a solid example of predicting the amount of salvage and waste materials for EoL buildings based on the database of 2,280 building demolition records. Deep learning-based machine learning approach [36] was adopted to achieve high reliability and accuracy of prediction based on historical project data.
- From existing data sources, waste estimates can then be conducted in early project stages assisted by digital tools (e.g., BIM). More C&D WM and deconstruction related activities beyond waste generation estimate could be conducted. More functionalities could be developed in new digital prototypes, for example, simulation of different demolition or deconstruction strategies [24] to allow comparisons and decision making.
- Implementation of digitalization for C&D waste minimization including deconstruction planning can be better set in the context of the latest practices of the built environment, for instance, OSC or modern method of construction. OSC

has been widely recognized of its inherent connection to digital technologies or platforms (e.g., BIM) [37,38]. OSC method, by reducing on-site work and promoting modularity and standardization of M/C, makes it easier for digitalization (e.g., RFID) to capture, store, and track the flow of M/C. Digital approach such as IoT fits the need of the life cycle monitoring of OSC facilities, including the real-time attributes of individual M/C.

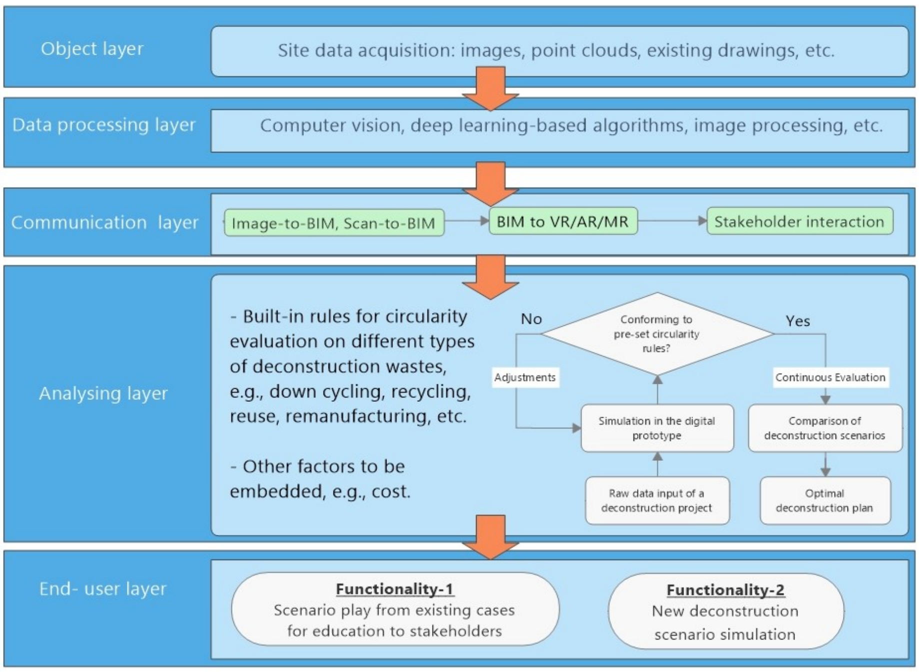
4 Methodological Framework of Digitalization for Deconstruction

It should be justified that digitalization is one approach to enhance C&D WM, but not as the purpose. The heterogenous materials/components (M/C) stored in "bank" (i.e., built assets) have their flows in a dynamic process across the building or infrastructure life cycle. The EoL built facilities to be deconstructed or reconstructed are commonly demolished with all sorts of M/C unseparated. Sorting or categorizing the heterogenous M/C is still an unsolved challenge under CE. Depending on the level of circularity defined in [39], such as recycle, repair, remanufacture, reuse, etc., sorting level of M/C at EoL built assets could vary. Digitalization, in the forms of various information and communication technologies, could become the enabler targeting existing challenges such as the sorting of different categories of M/C. Emerging technologies platforms such as IoT fits the application of the bespoke material passport (MP), which describes the documentation of material composition [40] to allow evaluation of M/C circularity and tracing material flow. Following the principles of CE and MP, deconstruction, although at the EoL built facilities, may not be necessarily the EoL for individual M/C. Digitalization plays a key role in implementing MP in terms that: 1) it promotes DfD in the early project stages to engage multiple stakeholders including architects, engineer, end-users, etc.; 2) it enables real-time tracking and monitoring of M/C at different life cycle stages for the up-to-date C&D WM; and 3) it enhances the tracing and tracking of individual M/C to acquire the information of M/C properties. This would be critical in deciding-making of adopting deconstructed M/C because architects/engineers need to know the quality and property of M/C from their previous life cycle. For example, the source of recycled or reused M/C is defined as "parent" in several existing studies [41,42] adopting recycled aggregates from the demolished concrete. The information of this "parent" (i.e., source) is important to know the engineering properties or quality of the recovered M/C for circular use.

The prior summary of literature review reveals several areas for continued research in adopting digitalization for C&D WM especially deconstruction, including the need of an integrated system to connect different digital software and hardware, multi-stakeholder experience and feedback, extending CE philosophy and life cycle in a "grave"-to-"cradle" approach to promote deconstruction, the need to address aging or existing built facilities without BIM-based data source, the quality and source of raw data of M/C attributes, key activities or functionalities in the digital system for deconstruction, and setting digital deconstruction in the emerging built environment practices such as off-site construction (OSC). These areas for continued research and development are inter-connected, for example:

- The need of an integrated system should be tested and validated by a variety of stakeholders;
- Deconstruction process would engage more stakeholders including but not limited to those involved in operation and maintenance of existing built assets;
- The lack of BIM-formatted data source in those existing built assets determines that BIM would not be the only digital platform for implementing deconstruction, but to be integrated with other digital technologies, such as laser scanning to allow scan-to-BIM;
- The different ways to obtain raw data lead to the discussion of raw data quality and the data source, such as historical data from archived projects at the company, organization, or industry levels;
- The needs and functionalities in an interoperable digital system would enable a variety of key activities to be conducted for deconstruction beyond C&D waste generation estimate;
- The practice of deconstruction or other C&D WM work should not be separated from the latest emerging trends of built environment, such as OSC which is expected to lower C&D wastes as compared to traditional site-based construction.

Based on the limitations and trends of these inter-related research areas, a schematic diagram is initiated to demonstrate one example of methodological framework in adopting a digital prototype for deconstruction planning as seen in Fig.1.



Note: VR, AR, and MR stand for virtual reality, augmented reality, and mixed reality respectively.

Fig.1. Schematic diagram of the Digital Prototype for Deconstruction Planning

The methodological framework shown in Fig.1 consists of five layers:

- The first layer named object layer is mainly for raw data collection in various ways, for example, site survey using laser scanning, existing 2D-based drawings, and site images, etc.
- The second layer named data processing layer is for processing of raw data, for example, image processing of photos taken on site.
- The third layer named communication layer engages more technologies, including registering point cloud from laser scanning to BIM, converting 2D CAD drawings into digital models, and further from BIM to VR, AR, MR aiming for multi-stakeholder engagement.
- The fourth layer named analyzing layer with built-in rules would allow the simulations and comparisons for decision-making of different deconstruction strategies. Pre-set criteria for comparisons are to be embedded into the system, e.g., cost, energy, and carbon associated with individual M/C.
- The fifth layer named end-user layer is initially designed with two functionalities. The first functionality is based on learning from past projects for educational purposes. Engaged stakeholders can learn the different deconstruction strategies beyond demolition, and the attributes of different M/C. The new deconstruction scenario allows stakeholders to compare different deconstruction strategies available to decide the optimal option. Final semantic reports will be generated related to each demolition strategy with simulation results according to the pre-set criteria in the fourth layer. Assisted by wearable technologies, end-users will also be able to experience an immersive environment of different deconstruction scenes.

Besides the example of methodological framework displayed in Fig.1, furtherance of knowledge and practice for adopting digitalization in deconstruction following CE principles is recommended herein, specifically: (1) moving from framework to case studies to test the transferability of the initiated prototypes; (2) updating with project or benchmarked data to test the accuracy and performance of digitalization in deconstruction; (3) extending digitalization for deconstruction of existing or aging assets; (4) increasing the robustness of existing digital platforms in being applied crossing project types (e.g., large-sized commercial projects); and (5) improving the automation level from BIM to digital twin, IoT, and Artificial Intelligence for smart decision-making.

5 Conclusion

Aiming to uncovering the current research worldwide in adopting digitalization for construction and demolition (C&D) waste diversion following circular economy (CE) principles, this study firstly reviewed existing studies related to CE, digital application in C&D waste management (WM), and deconstruction as alternative to the traditional demolition. Limitations and trends were summarized following the literature review, leading to an initiated methodological framework (MF). Specifically seven areas were identified for continuous work, including: the need of an integrated system to connect different digital or data technologies (e.g., imaging processing, machine learning, laser scanning, BIM, and VR, etc.), multi-stakeholder interaction to the digital system, a "grave"-to-"cradle" approach to promote deconstruction, the need to address aging or existing built assets without BIM-based data source, the quality and source of raw data of material or component attributes, key functionalities in the digital system for deconstruction beyond waste estimate, and setting digital deconstruction in the emerging built environment practices such as modern method of construction. Based on these interconnected areas of continued research, an initial MF was demonstrated to display five different layers from raw data collection, data processing, communication, analytics, to end-user adoption. The current MF will lead to future work in developing the digital prototype for deconstruction, test & trial through case studies, and updates. The current study will also lead to more work involving Internet-of-Things and Artificial Intelligence as emerging concepts for CE-based C&D WM, for example, smart decision making for stakeholders to identify the optimal deconstruction strategy based on cost, carbon, and energy performance.

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