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DIGITAL TECHNOLOGIES AS ENABLERS OF COMPONENT REUSE: VALUE-CHAIN PERSPECTIVES IN CONSTRUCTION AND MANUFACTURING

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ABSTRACT

Prabhat Kiran Thakuri: Digital Technologies as Enablers of Component Reuse: Value Chain Perspectives in Construction & Manufacturing
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Our planet is experiencing climate emergency due to the overconsumption of natural resources and ever-increasing carbon footprint. The construction and manufacturing industries are by far the biggest contributors to this grim situation. Hence, it is of paramount importance that the current economic model in those industries shifts from conventional linear to circular. Among the different circular economy (CE) approaches, adopting the component reuse practices is more imperative; because, after reduce, reuse is considered to be the least resource and energy intensive CE principle. With regard to transformation of the construction and manufacturing industries towards component reuse, digitalization could play a major enabling role. However, how the digital technologies such as BIM, digital twin, IoT (sensors and RFIDs), and robots could facilitate the component reuse practices is still an underexplored field of study. Additionally, the studies thus far in this direction lack the integrative approach both from multi-technology and multi-stakeholder perspectives. Therefore, the objective of this research is to investigate the perspectives of value chain actors, in construction and manufacturing, on how the digital technologies can advance component reuse practices.

To address the research objective, this study employs qualitative research methodology and therein, multiple case study method. For the selection of most relevant cases, purposive sampling strategy was used. As a result, ten cases were selected, out of which, six are from the construction industry and the remaining four belong to manufacturing industry. To garner the primary data from those cases, semi-structured elite interviews were carried out. Subsequently, the data analysis process proceeded from within-case analysis to cross-case analysis. Finally, the findings from construction industry were juxtaposed to the findings from manufacturing industry, in order to examine the similarities and differences in how the digital technologies can advance component reuse practices in each industry.

The findings of this study suggest that both the construction and manufacturing industries are becoming more perceptive to the need circular economy transformation. They recognize that the digital technologies are de facto the cornerstones in their efforts to adopt component reuse practices. The results demonstrate that collectively the BIM and IoT in construction, similar to digital twin and IoT in manufacturing, enables several component reuse practices- namely, DfDR, predictive maintenance, logistics & inventory management, quality & lifecycle assessment, and component disassembly planning. In addition, a few digital technology-enabled reuse practices were identified, that are peculiar to each industry. Robots, for instance, were recognized for the potential to partially automate some repetitive processes in construction industry, but that was not the case in manufacturing. Nevertheless, this study indicate that, for the technologies to be optimal in their enabling role, their current technological capabilities need to be developed further in the future.

This study enriches the literature stream in circular economy and digitalization both in terms research methodology and findings. By taking a broader and integrative stance and through comparative study of two industries, this study validates several previous findings and also proposes novel findings of its own. To the practitioners the findings will provide comprehensive insights that may be useful in their efforts to adopt or foster digitalization in component reuse context. Finally, this study identifies a few directions for future research that may result in promising outcomes.

Keywords: digital circular economy, digitalization, component reuse, remanufacturing, sustainability, value chain

PREFACE

Circular economy and sustainability has been my fascinations for a long time. Therefore, writing a thesis on this domain has been both illuminating and fulfilling. The thesis writing process has been rather fruitful to myself, but I suppose the findings in this research will be insightful also to the academics and practitioners.

I am particularly grateful to my supervisor Dr. Leena Aarikka-Stenroos for providing this invaluable opportunity and offering enlightening guidance. Without her reviews and recommendations, this work would not have ended up the same. Also, my especial thanks to Mr. Lauri Alkki for his encouragement and constant support. From onset to the completion of this thesis, his support has been unparalleled. I am also thankful to the entire CITER team for their help, be it direct or indirect. For the most part, I would like to express my sincerest gratitude to all case company representatives who provided the most valuable inputs for this study. Without them imparting their knowledge, this thesis could never achieve its essence.

Finally, my utmost appreciation goes to my family and friends, for they have always been the source of joy and motivation in all my endeavors.

Tampere, September 2022

Prabhat Kiran Thakuri

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LIST OF SYMBOLS AND ABBREVIATIONS

AR	Augmented Reality
BIM	Building Information Modelling
BoL	Beginning-of-Life
CAD	Computer Aided Design
CE	Circular Economy
CPD	Circular Product Design
D-DAS	Disassembly and Deconstruction Analytics System
DfD	Design for Deconstruction/Disassembly
DfDR	Design for Deconstruction/Disassembly and Reuse
DfMA	Design for Manufacturing and Assembly
DPP	Digital Product Passport
DSP	Disassembly Sequence Planning
DTs	Digital Technologies
DwRC	Design with Reused Component
EC	European Commission
EoL	End-of-Life
EPC	Electronic Product Code
EPD	Environmental Product Declaration
ESG	Environmental, Social, and Governance
EU	European Commission
EV	Electric Vehicle
HRC	Human-Robot Collaboration
IFC	Industry Foundation Classes
IMDS	International Material Data System
IoT	Internet-of-Things
IPR	Intellectual Property Rights
LCA	Lifecycle Assessment
MP	Material Passport
PEID	Product Embedded Information Device
PSS	Product-Service System
RFID	Radio Frequency Identification
ROD	Robot Oriented Design
RoI	Return on Investment
STCR	Single Task Construction Robots
UHF	Ultra-High Frequency
VR	Virtual Reality

1. INTRODUCTION

1.1 Background of the Study

The dramatic increase of world population has led to several social and environmental concerns that can only be addressed by rethinking our existing economic model. On one hand, the demand for products and services have been increasing, leading to overconsumption of natural resources; on the other hand, disposal of wastes and greenhouse gas emission have been increasingly jeopardizing the entire biosphere of the planet. While circular economy (CE) as an alternative economic model has been gaining attention over the years (Geldermans, 2016; Ghisellini et al., 2018), it has not yet materialized enough in practice.

Interestingly, digital technologies possess the potential to transform the CE principles into a practical reality, at mega-scale or systemic level across industries and value chains (Cagno et al., 2021; Trevisan et al., 2021). Whereas the previous studies mostly focused on use of digital technologies for reducing and narrowing resource use (Laskurain-Iturbe et al., 2021; Trevisan et al., 2021), it is conceivable that their functionalities could advance the component reuse practices as well, for instance through visibility of resource availability, transparency, collaboration or industrial symbiosis, and knowledge sharing. Nevertheless, further studies are required to substantiate how different value chain actors can use digital technologies to enable the component reuse practices.

The fundamental idea of circular economy is the cradle-to-cradle or closed-loop economic model whereby, materials at their end-of-life are utilized for creating value, instead of disposing them as waste (Ellen MacArthur Foundation, 2013; Bassi & Dias, 2019). It contrasts the traditional linear economic model, i.e., take-make-consume-and-dispose (European Commission, 2014), that leads towards extreme pollution and potential resource scarcity (Raworth, 2017; Akanbi et al., 2018; Benachio et al., 2020).

The traditional economic theories put high emphasis on the economic prosperity but failed to establish its correlation with the natural environment. Rather, they emphasized the importance of economic prosperity, even at the cost of environmental integrity of the planet. The concept of circular economy, as illustrated in Figure 1, tends to overcome this fundamental incongruity between the economic growth and environmental well-being (Pomponi & Moncaster, 2017).

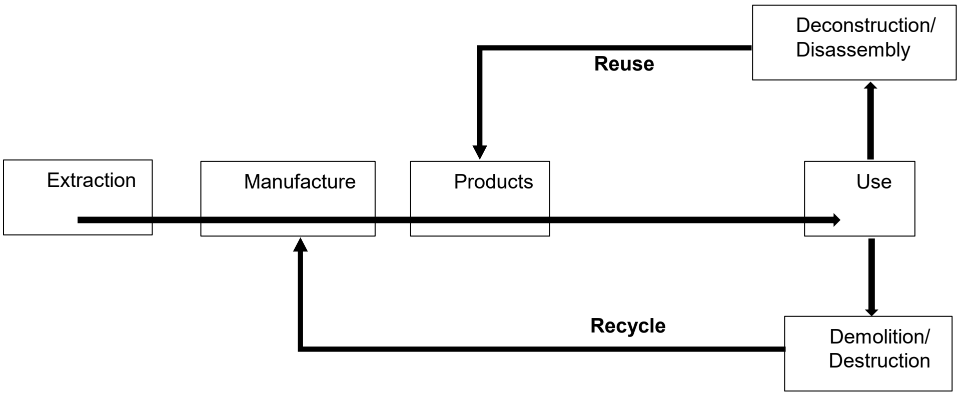

Figure 1. Closed loop lifecycle of materials (Based on Addis, 2006).

The circular economic model is fundamentally guided by the 3R principles which stand for reduce, reuse, and recycle (Kobe 3R Action Plan, 2008). First, the principle of reduction is primarily concerned with the reduction of material and energy consumption as well as waste generation through production and use of products (Feng & Yan, 2007). This is realized by optimizing the production and consumption efficiency both in design and practice (Su et al., 2013). Second, the principle of reuse implies the use of a product or component again again, without any other pre-processing, for same purpose it was originally produced for (European Union Directive, 2008/98/EC). Third, the principle of recycling implies reprocessing of products or components for production of new materials, either for the original or other purposes (European Union Directive, 2008/98/EC; Lu & Yuan, 2011; Ghisellini et al., 2018). The European Union Directive (2008/98/EC) Article 4 proposes the hierarchy of 3R principles, as illustrated in Figure 2, which prioritizes reduction over reuse and reuse over recycling.

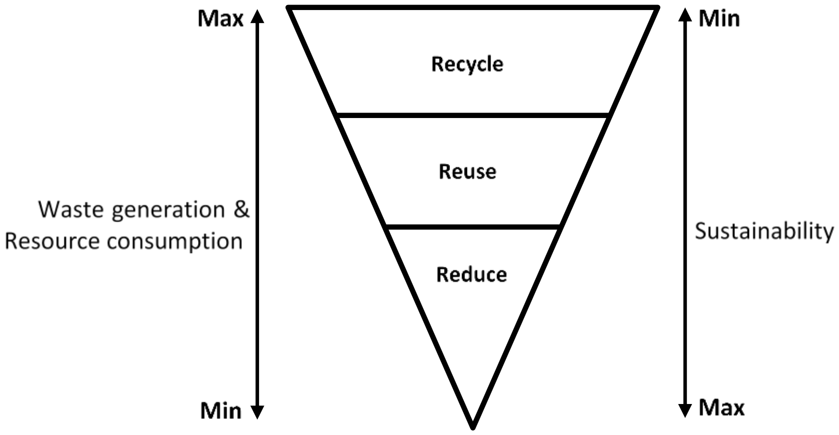

Figure 2. Hierarchy of 3R principles (European Union Directive, 2008/98/EC).

The principle of reduction is considered the leading circular economy principle (Su et al., 2013) because it aims to eliminate the very need for reuse and recycling (Ranta et al., 2018). However, the reduce principle is particularly a design principle that aims to reduce or eliminate waste generation already when designing a product, rather than managing or repurposing the waste when the product reaches its end-of-life stage. Therefore, the practical implication of this principle is limited from the perspective of existing buildings or products. While opting to the use of renewable energy, instead of non-renewables, and extending the product lifecycle are practical applications of reduce principle, it has virtually no role when the product reaches its end-of-life stage. This is where the reuse and recycle principles come in.

After reduction, the principle of reuse is considered more sustainable than the principle of recycling, because reuse requires less resource consumption for closing the material loop than recycling does (Lu & Yuan, 2011). However, reuse has not yet received enough attention in the academic studies as compared to recycling has. There could be a few reasons for this. First, for the purpose of reuse, products and components need to be recovered with highest possible material and structural integrity, which is not as strict a requirement for recycling. Particularly if the existing products were not designed with reuse in mind, then recovering the components with high integrity is quite challenging, if not virtually impossible. Second, the reuse of products or components requires a greater degree of planning than recycling does. Finally, reuse, in comparison to recycling, necessitate a higher degree of coordination among the value chain actors, which is a rather challenging endeavor.

Lately, different approaches to reuse, such as Design for Deconstruction/Disassembly (DfD); Design for Reuse (DfR); Design for Manufacture and Assembly (DfMA), and Circular Product Design (CPD) have been proposed as promising tools in construction and manufacturing (Smith & Hung, 2015; Geldermans, 2016; Sanchez, 2019; Rakhshan et al., 2020; Pinheiro et al., 2022). The concept of modular construction & manufacturing, in particular, have been a widely studied and practiced concept (Smith & Hung, 2015; Rose & Stegemann, 2018). Nevertheless, these practices to reuse predominantly focus on the design phase of new products and components rather than the in-use and end-of-life stages of the existing ones (Adamu et al., 2020). Consequently, it is imperative to study how different digital technologies could be utilized to facilitate the reuse practices throughout the value chain.

1.2 Research Objective, Questions and Scope

How digital technologies enable the practical reuse of components, from buildings and other products, is still an underexplored field of study. Traditionally, digital technologies have mainly been promoted as the tools to improve resource efficiency in the manufacturing and construction stages of value chain; however, their significance for reuse of the end-of-life components has been largely overlooked (Inacovidou et al., 2021). While digitalization are considered conducive in this regard as well (Pagoropoulos et al., 2017; Ucar et al., 2020; Liu et al., 2022), concrete studies are necessary to understand how they can facilitate the component reuse practices in reality.

For the simplicity and focus of the study, three different digital technologies are selected for the construction industry- namely, BIM, IoT and robotics. Similarly, Digital twin, IoT, and robotics are selected for the manufacturing industry. From this vantage point, this study aims to explore the perspectives of different value chain actors, to come to a common understanding of how the selected digital technologies enable component reuse practices across the value chain. However, before exploring how the digital technologies can advance component reuse practices, it is important to understand the value chain actors' motivations and challenges for component reuse. Consequently, following research questions are formulated for this study.

RQ1: What are motivations for component reuse in construction and manufacturing?

RQ2: What are the challenges of component reuse in construction and manufacturing?

RQ3: How can the selected digital technologies enable component reuse practices in construction and manufacturing?

RQ4: What are the similarities in the use of selected digital technologies for component reuse, between construction and manufacturing?

As implied in the research questions, this study entails research in both the construction and manufacturing industries. To answer the research questions, this study employs both theoretical and empirical studies. For the theoretical study, an extensive literature review was carried out. Whereas, for the empirical study, a qualitative multiple case study method was employed.

First, the approach to literature review is integrative rather than systematic (Torraco, 2005). Under this approach, all the discovered articles are taken into consideration as potential source of information for the comparative evaluation. The literatures were accessed through several databases such as Elsevier, ProQuest, Sage Journals Online, EBSCO, IEEE Electronic Library, SpringerLink, Emerald, JSTOR, and Google Scholar. In addition, google search was used to find other relevant publications.

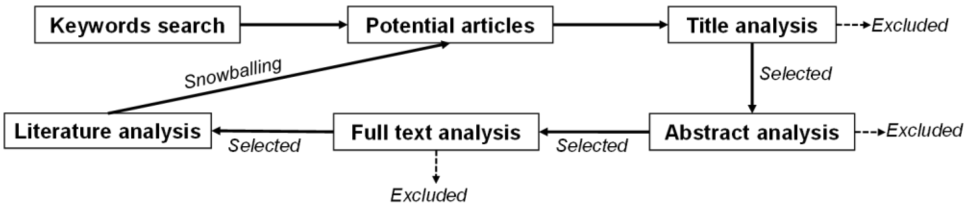

Figure 3. Literature review process.

Second, the multiple case study approach entails 10 semi-structured interviews, followed by rigorous analysis and abstraction. The selection of cases was purposive, allowing researchers to select the most relevant cases, which aids significantly to the inferential process (Seawright & Gerring, 2008).

In this study, the scope, i.e., inclusion-exclusion criteria (Chauhan et al., 2022), is defined from three different perspectives. The first is the scale perspective. This study aims to create an understanding of industrial or large-scale component reuse. The second is the technology perspective. For both the simplicity and focus, only a few promising digital technologies are selected for the study. The third is the value-chain perspective. Since reuse of components necessitate a systemic change that cannot be accomplished with disparate efforts but with integrative approach in the value chain, this study incorporates the perspectives of different vale chain actors.

1.3 Structure of the Study

Rest of the chapters are organized as follows. First, Chapter 2 provides an extensive review of literatures that are directly or indirectly related to the research questions. For instance, concepts of component reuse in construction and manufacturing are discussed as well as their benefits and challenges. Also, selected digital technologies and their potential contribution to component reuse, both in construction and manufacturing, are outlined. Second, Chapter 3 discusses the research mythology and process used for this study. Next, Chapter 4 compiles the results and analysis from the empirical study; research questions are answered based on findings from the case studies. Finally, Chapter 5 presents the conclusive summary of key findings, along with theoretical contribution, managerial implications, research limitations and directions for future research.

2. THEORETICAL BACKGROUND

2.1 Overview of Digitalization for Reuse

Digital technologies (DTs) are considered to be significant drivers of circular economy in several sectors, including the construction and manufacturing industries (Kristoffersen et al., 2020; Walden et al., 2021). Traditionally, they are recognized as means to facilitate circular economy by enabling smooth communication among the value chain actors and by facilitating predictive or preventive maintenance. However, their implications for management of end-of life products is a novel field of study which needs to be explored further (Pagoropoulos et al., 2017).

The functionalities of digital technologies, such as data gathering, transfer, storage, and analysis (Ucar et al., 2020) could foster circular economy practices such as reuse and recycling. In a systematic literature review, Liu et al. (2022) concur that different circular economy practices are enabled by the digital functions, namely the data collection & integration, data analysis, and automation. Antikainen et al. (2018) argue that digitalization can close the material loops through accessing and utilizing real time information on the availability, location, and the performance of the products or components. Additionally, Adamu et al. (2020) emphasize that the wider adoption of digital technologies can facilitate deconstruction or disassembly which, in contrast to the traditional demolition, fosters the component reuse practices.

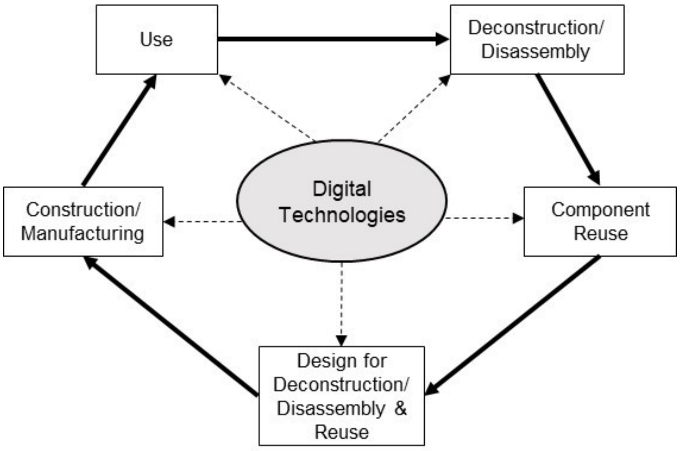

Figure 4. Role of DTs in closing material loop (Based on Addin, 2006).

Several digital technologies possess the potential to contribute towards the wider adoption CE principles (Adamu et al., 2020). However, in this study, digital twin, IoT, and robotics are selected to be studied. First, digital twin is a technology that has lately had tremendous attention in terms of its ability to facilitate reuse (Charef et al., 2019; Wang & Wang, 2019; Chen & Huang, 2020; Sanchez et al., 2021; Walden et al., 2021). Across industries, it is known with different names, such as digital product passport (DPP), environmental product declaration (EPD), building information model (BIM), and international material data system (IMDS). Nevertheless, simply put, digital twin is digital 3D model of a physical product that stores and visualizes the structural and material attributes of the product. This ability to store valuable information is the fundamental reason why digital twin could be pivotal for facilitating component reuse practices.

Second, IoT is one of the interesting technologies with the potential to accelerate reuse practices (Bertin et al., 2019; Khan et al., 2021). It is even considered as the most critical digital tool for advancing circular economy in several sectors (Antikainen et al., 2018). Awan et al. (2021), for instance, emphasize that applications of IoT extends beyond the automation of production and services, to recovery and reuse of components when products reach their end-of-life stages. This finding is further substantiated by other researchers, for instance through an industrial research by Pinheiro et al. (2022).

Finally, robotics is a promising technology that could be pivotal for making component reuse practices effective and efficient (Lee et al., 2015; Kerin & Pham, 2019; Liu et al., 2022). Delgado et al. (2019) and Pradhananga et al. (2021) suggest that the applications of robotics in construction have mostly been associated with the upstream activities, such as prefabrication and assembly, rather than at the end-of life stages. However, the positive implications of robotics for reuse cannot be ignored. For instance, since the component recovery process can be repetitious, labor intensive, and even unsafe, use of robotics could be fruitful in the component recovery process (Lublasser et al., 2016). In the manufacturing industry, Sarc et al. (2019) and Aziz et al. (2021) make similar remarks in terms of the applications of robotics for reuse.

2.2 Reuse as a CE Practice in Construction Industry

According to United Nations Department of Economic and Social Affairs (2020), 47 percent of the world’s population used to live in urban areas, which has grown to 55 percent in 2018, and it is going to grow to 60 percent by 2030. This rapid urbanization, around the world, has resulted in increasing number of building constructions and demolitions.

Globally, the construction industry is considered as one of the major contributors to resource consumption and waste generation (Won & Cheng, 2017; Ajayi et al., 2017; Pimentel-Rodrigues & Siva-Afonso, 2019). Consequently, the consumption of virgin resources for building constructions and the disposal of demolition waste have become major concerns around the world (Rocha & Sattler, 2009; Cheng & Ma, 2013; Behera et al., 2014). According to Lee et al. (2015), the construction and demolition waste account for 30 to 80 percent of the total waste in countries around the world.

Several studies have recognized the need for closing the loop in construction sector for protection of environment and efficient resource management (Li, 2008; Rocha & Sattler, 2009; Koshiro & Ichise, 2014; Xuan et al., 2016; Hopkinson et al., 2019). While there are several ways to close the material loop, reuse should be prioritized because it is considered to be more resource efficient in comparison to recycling (Geyer et al., 2002; Ness et al., 2015). The waste Framework Directive, Article 4 (European Union Directive, 2008/98/EC), has also mandated a waste hierarchy which concurs that reuse shall be prioritized over recycling. While the framework prioritizes reduction over reuse, the reduction potential in construction is substantially low (Nordby, 2019).

As a result of an extensive study, Huuhka et al. (2015) contend that reuse not only reduces the carbon footprint but also reduces new construction costs by 20 to 30 percent. This implies that reuse can be the most effective CE approach, both environmentally and economically. Despite the immense benefits of reuse, recycling has remained the dominant means of CE application in the construction industry (Tam & Tam, 2006; Ness et al., 2015; Hopkinson et al., 2019; Rakhshan et al., 2021). Though reuse has not gained enough momentum in practice (Hradil et al., 2014), it is indubitable that it should become a priority in the future.

While the reuse of whole buildings is the most effective approach from circular economy perspective (Galvez-Martos et al., 2018), it is not always a possibility. In such cases, reuse of building components and materials is the second-best alternative. Therefore, buildings at their end-of-life stages should be approached as material or component banks, allowing deconstruction for reusable component recovery, instead of destructive demolitions (Rose & Stegemann, 2018; Hopkinson et al., 2019). As Forghani et al. (2021) emphasize, the component reuse in the construction sector is a critical driver for the reduction of construction and demotion waste.

2.2.1 Structural Components Reuse

Structural components are also commonly known as the load-bearing concrete elements that constitute the superstructure of a building, such as beams, columns, and slabs. Even though the service life of structural components is considered to be much longer than that of other building components (Fivet, 2019), structural component reuse is not a common circular economy practice just yet (Arora et al., 2020). Brutting et al. (2019) concur that the residual value of structural components has not been utilized well enough, when buildings reach end of their functional life.

The reuse of structural components, compared to other components or materials, has the most substantial potential to reduce material, energy, and resource consumption because those components are often material and manufacturing intensive (Brutting et al., 2019; Bertin et al., 2020). Consequently, several studies have recognized the importance of EoL structural components, for fully exploiting their residual life-cycle value (Gorgolewski, 2008; Hradil et al., 2014; Tingley et al., 2017.)

In addition to the obvious environmental benefit of reusing structural components, i.e., the reduction in consumption of virgin resources, water, and energy (Pongiglione & Calderini, 2014), there are other valuable benefits of reuse. For instance, the affordability of reused structural components can be a driver for saving costs for the customers (Rakhshan et al., 2020), particularly desirable among the low-income customers (Chini & Bruening, 2003). Moreover, recovering and reusing the structural components can provide a green image for the companies (Chinda & Ammarapala, 2015), which can even be turned into a competitive advantage.

To advance the reuse practices of structural components, it is critical that different stakeholders are willing to collaborate and make integrative efforts. The construction value chain actors, such as designers, demolition contractors, component manufacturers, constructors, and end-customers, play key role in making reuse of structural components a practical reality (Rakhshan et al., 2020). Interestingly, a study conducted in Finland by Hradil et al. (2014) suggest that the professionals and academics alike have rather positive attitude regarding the reuse of structural components. With climate adversaries and resource scarcities lurking at the horizon, it is presumable that the professionals and academics around the globe share the same attitude.

Fundamentally, there are three activities that are crucial to be optimized or adapted for the sake of structural component reuse, namely design, prefabrication, and deconstruction. First, Design has paramount implications as component reuse practice. On one hand the design of new components can facilitate their future deconstructability and reusability (Design for deconstruction and reuse), while on the other hand the design of new buildings can take into account the use of old components (design with reused components).

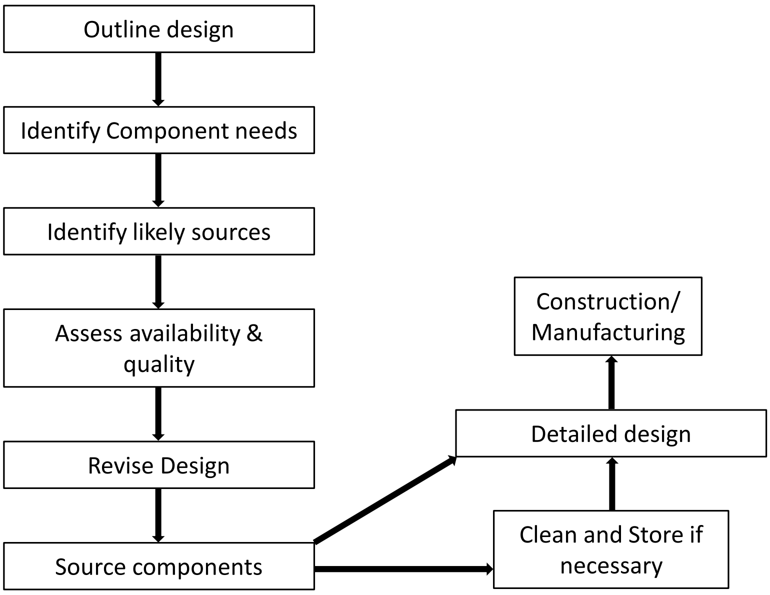

Figure 5. Reuse of components: Designer's perspective (Based on Addis, 2006).

Often the designing work is carried out separately by architects, precast concrete element manufacturers, and constructors (Dave et al., 2013). The diverse designs provide different yet complementary information about the building components. While the designs are created separately, all designs should take into consideration how reused elements can be incorporated into the new building construction and how new buildings components can be demounted and reused in the future. Consequently, the designs should not only provide the graphical representation of the building and components, but also associate all relevant information such as structural attributes, material and mechanical characteristics, installation and maintenance guides, warranties, ownership, and other editable life-cycle information such as location, age, quality and performance (Dave et al., 2013; Minunno et al., 2018). Moreover, when designing a building with reused elements, it is important to have a level of flexibility and adaptability in the designs (Gorgolewski, 2008). To engender these capabilities through design, digital technologies could play a significant role.

Second, prefabrication or off-site component manufacturing is an important prerequisite for structural component reuse (Iacovidou et al., 2021). Precast concrete manufacturers are increasingly manufacturing prefabricated components, particularly post-emergence of modular thinking in manufacturing. The prefabricated components are considered not only better quality than their cast-in-situ counterparts but also safer and sustainable (Kamali & Hewage, 2016; Lie et al., 2022). On one hand the off-site production of structural components is time and cost efficient, while other hand they are effective in reducing potential construction waste (Tam et al., 2006, Navaratnam et al., 2019).

While precast components are easy to install or assemble at construction sites (Mostafa et al., 2020), it is important that they are also durable, adaptable, and easily dismountable when buildings reach end-of-life (Fivet, 2019). Moreover, it is important that the precast concrete elements are free from toxic chemicals so that they are safe to disassemble and use in second life (Minunno et al., 2018). Additionally, the components need to be traceable, and the manufacturers should have information management system to store and update relevant life-cycle information of the components.

Finally, deconstruction or disassembly is one of the most significant activities when it comes to reuse of components (Forghani et al., 2021). Also known as the reverse construction, deconstruction is a process of dismantling or disassembling a structure so that the valuable components of the building can be recovered and used in second-life applications (Akbaieh et al., 2020).

In construction sector, the deconstruction is carried out by demolition contractors who are traditionally habituated to (destructive) demolition. One of the reasons why demolition is preferred over deconstruction by those companies is the perception that demolition is cost-efficient in terms of labor and time (Munroe et al., 2006). Be that as it may, however, several studies assert that when the salvage value of recovered components is considered, deconstruction is in fact more cost-coefficient or lucrative than the demolition (Chini & Bruening, 2003; Rocha & Sattler, 2009; Rios et al., 2015). Moreover, deconstruction, contrary to demolition, is an effective approach of waste diversion and therefore, environmental wellbeing (Bougrain & Laurenceau, 2017; Adamu et al., 2020).

Munroe et al. (2006) assert that deconstruction can divert 80-90% of potential construction wastes to reuse and recycling, that would otherwise be disposed to landfill (Munroe, et al., 2006). However, the proper order of disassembly process is critical for recovering the components without damage (Chini & Bruening, 2003). Damage to the structural components, when recovering them, can make them unusable (Rios et al., 2015). Therefore, the component reuse can only be maximized by ensuring their careful disassembly (Hradil et al., 2014).

It is also critical to acknowledge that the interconnection or interdependence of building components can affect the deconstruction process substantially (Huuhka et al., 2015). Consequently, effective deconstruction requires information visibility regarding the adhesion, joining positions, and structural transitions of the components (Lublasser et al., 2017). Additionally, the interconnection between the structural components should be such that they can be disassembled without incurring damage (Nixon, 1976).

It is important to note that total deconstruction of buildings might not be economically and technologically feasible, for instance due to limitations in time, resources, and toxic contamination. In such cases, selective deconstruction should be opted. However, that too is not free from challenges. It is particularly challenging with the old buildings, because most of the existing buildings today were not designed with disassembly or component reuse in mind (Dunant et al., 2017; Xing et al., 2020). Nevertheless, digital technologies are conceived to possess the capabilities that can effectuate deconstruction of existing as well as new buildings.

2.2.2 Challenges to Structural Components Reuse

The market for reused structural components do not exist and the few that exist are not large enough (Gorgolewski, 2008; Akinade et al., 2020). This implies that despite the huge potential of structural component reuse to optimize resource utilization and efficiency, it has not yet been a driving CE methodology in construction industry (Akanbi et al., 2019). Studies recognize several reasons for this. One of the prominent reasons is that most of the existing buildings today were not designed for disassembly or component recovery at end-of-life, which poses both technical and economic challenges for reuse of structural components (Huuhka et al., 2015; Xing et al., 2020). Moreover, the nonexistence or lack of original design documents is a major hinderance for the component reuse, because it creates an ambiguity how the components can be deconstructed in a safe and efficient manner (Bertin et al., 2019; Akinade et al., 2020).

When discussing the challenges to structural component reuse, researchers have quite often stressed about the lack of standards and legislation for building materials and components (Hradil et al., 2014; Park & Tucker, 2017; Akinade et al., 2020; Anastasiades et al., 2021). Additionally, Rocha and Sattler (2009), as well as Iacovidou et al. (2021), for instance, observe that the fundamental problem lies with the resistance of different stakeholders to transition from existing linear economic model to the circular. The resistance could be due to either the lack of trust on performance and functionality of reused components (Ness et al., 2015; Rios et al., 2015; Dunant et al., 2017; Rakhshan et al., 2021) or the hesitation to invest time and money for quality control and recertification of the recovered components (Dunant et al., 2017; Hopkinson et al., 2019).

Lack of component traceability (Whittaker et al., 2021) and inadequate information flow (Rocha & Sattler, 2009) in the value chain have been also emphasized as major challenge for component reuse. Bertin et al. (2019) suggest that it is not only the lack of physical traceability of components but also the lack of traceability of their material characteristics that inhibit the reuse practices. Moreover, other obstacles include variability of the volume, lack of dimensional or functional consistency, and limited availability of reused components (Rocha & Sattler, 2009; Dunant et al., 2017; Whittaker et al., 2021).

When considering the reuse of recovered components into new buildings, it is important to note that the markets for purchase and sales of reused building components are yet to develop (Rose & Stegemann, 2018). Also, unlike conventional design method where building designers first create a design, followed by materials and components procurement, the reuse of structural components require the designers to first check on the availability of components and their properties, followed by optimized designing process to effectively utilize them (Addis, 2006; Bertin et al., 2019). This shift requires the designers to incorporate high level of flexibility and adaptability in the designs (Gorgolewski, 2008). This transition from the conventional design practice can be a challenging endeavor (Brutting et al., 2019; Kozminska, 2019).

Furthermore, Whittaker et al. (2021) have emphasized that there is a lack of effective technologies to facilitate the structural component disassembly of existing buildings. However, some digital technologies might have the potential to overcome this challenge as well as many other challenges mentioned above. In this regard, BIM, IoT, and robotics in particular are discussed in the following sections.

2.2.3 Digital Tools for Structural Components Reuse

Digital technologies, in the past, have mainly been promoted as a tool to improve resource efficiency in the manufacturing and construction stages of value chain; however, their significance at the end-of-life stage of structural components has been overlooked (Inacovidou et al., 2021). However, with the gradual shift of construction industry from linear to circular economic model, digitalization is considered as one of the key enablers of component reuse practices (Carra et al., 2018). Some of the previous literatures in this direction, selected for literature review, are presented in table below.

Table 1. Synthesis of relevant literatures discussing the role of digital technologies (DTs) in structural component reuse.

Author	**Research Type/Context/Setting**	**Reuse Aspect Addressed**	**DTs**	**Relevant Key Ideas/Findings/Propositions**
BIM focused				
Cheng & ma, 2013	Applied case study in Hong Kong, Prototype development	*Deconstruction planning*	BIM	Framework for BIM based system, using BIM application programming interface (API), that can extract and process the information of components in BIM to estimate type and volume of wastes
Akbarnezhad et al., 2014	Case study	*Deconstruction planning*	BIM	Framework for identifying the economically and environmentally most efficient BIM-based deconstruction strategy from a set of predefined strategies. Assessment of the strategies are based on the automatic evaluation of deconstruction-related attributes of components as well as the costs, emissions and energy associated to deconstruction activities
Akinade et al., 2017	Focus group interviews with UK professionals	*DfDR, Deconstruction planning*	BIM	Adoption of BIM can significantly improve the performance of design for deconstruction (DfD) tools. BIM based DfD tools can have functionalities such as improved stakeholders' collaboration, recoverable material identification, deconstruction planning and visualization, simulation and performance analysis of EoL strategies, buildings lifecycle management, and compatibility with BIM software
Lu et al., 2017	Literature review, Prototype development	*DfDR*	BIM	Framework of computational BIM to enable circular economy; Information readiness and computational algorithms are indispensable to such computational BIM.
Akanbi et al., 2019	Case Study	*DfDR, Deconstruction planning*	BIM	Framework for extending the software capabilities of BIM with disassembly and deconstruction analytics system (D-DAS) to evaluate building designs for end-of-life component circularity
Bertin et al., 2019	Concept development	*DfDR, Design with reusable components*	BIM, IoT, Database	BIM framework development to associate new parameters of building components: mechanical information, material durability & ageing behavior. Integration of such BIM to IoTs and Database for LCA of components and enabling deconstruction & reuse
Adamu et al., 2020	Literature review	*DfDR, Deconstruction planning*	BIM, IoT, Image processing, Laser scanning, Data analytics, Machine learning	Methodological framework of a digital prototype for deconstruction planning of new and existing buildings; the framework has five layers that consist of data collection, data processing, communication, data analytics, and end user adoption. Among others, laser scanning, image processing, CAD, IoT, BIM, VR/AR, data analytics and machine learning technologies are critical constituents of the digital prototype.

Akbarieh et al., 2020	Extensive literature review	*DfDR, Deconstruction planning, Design with reusable components*	BIM	There is tremendous potential for BIM-based EoL such as DfD, deconstruction, and EoL LCA, among others. However, the challenge is lack of common or globally applicable BIM-based EoL frameworks, arising from dissonance between BIM tools and EoL tools and lack of Industry foundation classes (IFC) for information exchange
Berg et al., 2021	Applied case study (deconstructing nursing-home to reuse elements for school construction)	*Deconstruction planning*	BIM	Framework for BIM application in deconstruction activities: 3D existing conditions analysis, labelling reusable elements, and 4D deconstruction Simulation
Bertin et al., 2020	Applied case study (deconstructing high -rise buildings to reuse components in a medium-rise buildings)	*DfDR, Design with reusable components*	BIM, Database	BIM Framework development to transfer structural properties of load-bearing elements between the BIM modelling software, structural calculation software (for reuse optimization: reversible assembly, component traceability), and database (material bank) hosting the ready-to-reuse components
Sanchez et al., 2021	Case study, Prototype development	*DfDR, Deconstruction planning*	BIM	Framework for disassembly model in BIM, supported by other complementary softwares, through multi level-of-detail (Multi-LOD) of components. Identification of semantic BIM parameters or information requirements for selective disassembly planning
IoT focused				
Motamedi & Hammad, 2009	Applied case study of two High-rise buildings	*Component life cycle traceability, DfDR*	RFID, BIM	RFIDs as distributed BIM database: Permanent attachment of RFID tags to components such that they store design information of components retrieved from BIM and also accumulate lifecycle information.
Ness et al., 2015	Case study focused on structural steel components	*Component life cycle traceability, design with reusable components*	RFID, BIM, Sensor	RFIDs can track, locate, and import the lifecycle information of components and update them to BIM, allowing the networked stakeholders to assess them as per necessity. Particularly, designers can exploit the lifecycle information to design new buildings with the reusable components.
Iacovidou & Purnell, 2016	Literature review	*DfDR, Component life cycle traceability*	RFID, BIM	Use of RFID tags and BIM for gathering, storing and accessing the component properties can enable reuse
Pagoropoulos et al., 2017	Literature review	*Component life cycle traceability*	IoT, Big data analytics	Key functionalities of DTs to support circular economy are data gathering, data integration and data analysis. In this regard, IoTs, data management systems and big data analytics play key role.
Swift et al., 2017	Applied case study in two buildings in Australia	*Component life cycle traceability, DfDR, Design with reusable components*	RFID, BIM, Sensor	Use of RFIDs in integration to BIM allows bidirectional transfer of historical and life-cycle information of components such as original designs, installation date,

				maintenance history as well as changes in condition, performance, ownership, location, physical connection. The limited memory constraints of RFIDS can be overcome through data compression techniques.
Iacovidou et al., 2018	Extensive literature review	*Component life cycle traceability, DfDR, Deconstruction planning, Design with reusable components*	RFID, BIM	Integration of RFID and BIM could promote the reuse of structural components particularly because of RFIDs' capability to track and sort the component lifecycle information. Limitations of RFIDs include potential signal interference or obstruction, lack of common RFID technical standards and signal collision.
Ness et al., 2019	Applied case study, Prototype development	*Component life cycle traceability, Design with reusable components*	RFID, BIM, Cloud	Framework for cyber-physical data exchange system, connecting RFID, BIM, and Cloud-based data platform, to enable component reuse through tracking, transferring and managing lifecycle information (history, location, properties, & performance)
Robotics focused				
Cruz-Ramirez et al., 2008	Applied case study	*Robot assisted deconstruction*	Robotics, Image processing	Unfastening of screws can be carried out by robots that uses vision system based on multi-template matching and multi-frame integration techniques
Lee et al., 2015	Case studies	*Robot assisted deconstruction, DfDR*	Robotics, BIM	Systemized deconstruction with automated Single task Construction Robots (STCR) can be achieved by employing BIM data. Framework for Robot Oriented Design (ROD) for enabling efficient robotic deconstruction
Lublasser et al., 2016	Study of automated refurbishment & deconstruction in German & Japanese construction	*Robot assisted deconstruction*	Robotics, BIM, Sensor, Camera	Integration of different automated robotic systems, BIM, sensors, and cameras can enable component reuse of existing buildings that partially or completely lack digital information
Lublasser et al., 2017	Research in RFDRS project	*Robot assisted deconstruction*	Robotics, AI	Framework development for robot assisted adaptive deconstruction process of multilayered facade (robot setup, motion programming including force-controlled programming, and joint torque feedback)
Pan et al., 2018	Concept development	*Robot assisted deconstruction*	Robotics	Single task construction robots (STCR) and Automated/robotic on-site factories could be used to automate assembly and disassembly of components in/from high rise buildings
Lundeen et al., 2019	Case study and Experiments	*Robot assisted deconstruction*	Robotics, BIM, Sensor	Framework for autonomous motion planning and geometrically adaptive robots in construction workspaces, leveraging the sensors and BIM
Wilts et al., 2021	Research in 'ZRR for Municipal waste' project	*Waste sorting*	Robotics, RFID	Robotic waste sorting system based on artificial intelligence to enable circular economy

Building Information Model (BIM)

Building Information Model (BIM) is a virtual representation of a building, created digitally, that contains physical and functional information of the building's components and materials, such as composition, geometry, position, functions, quantity, costs, interconnectivity, and quality (Ghaffarianhoseini et al., 2017; Sanchez, 2019). In the past, BIM was predominantly used for validating and systematizing the construction designs before actual construction takes place (Volk et al., 2014; Rose & Stegemann, 2018). However, lately, it has been increasingly popular for its ability to support other functions such as procurement, prefabrication, scheduling, assembly, and maintenance activities (Azhar, 2011; Volk et al., 2014; Sanchez, 2019; Hilton et al., 2021). Moreover, though the application of BIM for reuse of structural components had previously been overlooked (Akbarnezhad et al., 2014; Akinade et al., 2017; Berg et al., 2021), lately the academia and practitioners are recognizing it as a technology that can advance the component reuse practices in an effective and efficient manner (Geldermans, 2016; Akanbi et al., 2019; Raouf & Al-Ghamdi, 2019; Sanchez et al., 2021).

Traditionally, BIM is known to provide digital information of the components that are often stored during the design and construction phase of a building. Such information would often remain static or un-updated throughout the building lifecycle (Iacovidou et al., 2018). Also, in the past, many of the constructors would not provide the BIM model to the end-users when the project is over (Eadie et al., 2013). Consequently, that would create an information gap when the components reach their end-of-life (Bertin et al., 2020; Sanchez et al., 2021). The gap is associated to the changes in component attributes such as ownership, location, quality, performance, and functionality of the components during their lifecycle (Geldermans, 2016; Iacovidou et al., 2021).

Nevertheless, lately, BIM has increasingly been recognized for its potential to facilitate the component reuse practices through its capability to create, share, exchange, and manage lifecycle information of components and materials (Motamedi & Hammad, 2009; Charef et al., 2019). BIM as lifecycle information repository, BIM-based design for deconstruction, BIM-based deconstruction, BIM-based Life cycle assessment are a few potential applications of BIM that can enable the circular economy practices such as component reuse (Akbarieh et al., 2020; Charef, 2022). Fundamentally, BIM enables component reuse by facilitating design, deconstruction, and information management. Figure 6 illustrates the constituents of a BIM model and its use for structural component reuse.

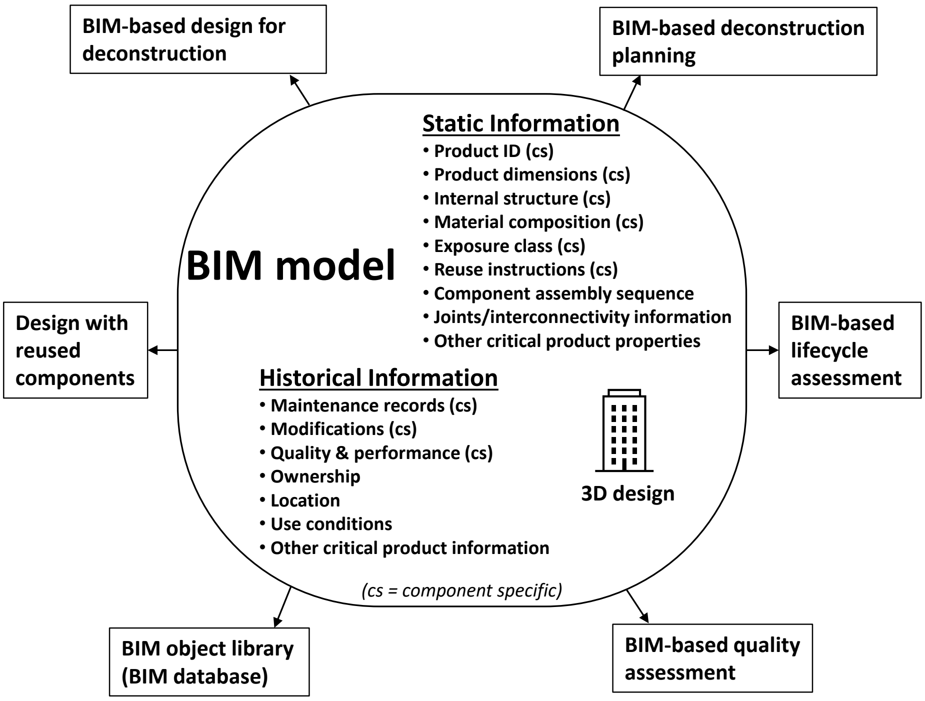

Figure 6. Synthesis of BIM and its applications for structural component reuse.

Sanchez et al. (2021) suggest that BIM, supported by complementary technology, can be used to create a disassembly model of buildings. However, for this, the BIM parameters need to be expanded to incorporate more variables or semantic information of the components. In their earlier work, Sanchez et al. (2020) point out the need to identify the critical component properties or indispensable information that need to be stored in the BIM. Along the same line, Bertin et al. (2019) propose that, when designing each structural components, the BIM should employ additional parameters such as mechanical behavior, material durability and ageing characteristics. Moreover, According to Charef et al. (2019), BIM should also be utilized as a tool to make the material composition of components transparent.

Researchers point out that if BIM has the record of component assembly sequence, then later on it can work as a guide for disassembly sequence planning. An effective and efficient component disassembly process is difficult to achieve when there is lack of information regarding the adhesions, joining positions, structural transitions, and bead patterns between the components (Lublasser et al., 2017). By storing such information into the BIM, the deconstruction process can be highly streamlined. This notion is substantiated in the studies by Forghani et al. (2021) and Sanchez et al. (2021) who observe that, for facilitating deconstruction and component reuse, it is critical to store detailed information about components and their physical interfaces and interdependence.

BIM based DfD tools can have functionalities such as improved stakeholders' collaboration, recoverable material identification, deconstruction planning and visualization, buildings lifecycle management, and simulation or performance analysis of EoL strategies (Akinade et al., 2017). For instance, Cheng & Ma (2013) emphasize that BIM can be used to readily estimate the material volumes that will be available at the end of building lifecycle. Akanbi et al. (2019) proposed a disassembly and deconstruction analytics system (D-DAS) as a part of BIM that would facilitate the evaluation of building designs to assess their material recovery potential. Berg et al. (2021) also demonstrated, in their case study, three different utilities of BIM for buildings deconstruction, namely the 3D existing conditions analysis; reusable elements labelling; and 4D deconstruction simulation.

Similarly, Akbarnezad et al. (2014) propose that the deconstruction related attributes of building components can be sourced from BIM into a data processor which then evaluates the data to identify the disassemblable components. Next, the data processor evaluates economic and environmental efficiency of different predefined deconstruction strategies to select the most efficient one. This assessment of the strategies is based on the automatic evaluation of cost, carbon, and energy performance of different deconstruction activities, as well as the deconstruction related attributes of components, such as recyclability, reusability, structural/geometrical properties, handling & installation guidelines; geographic locations; and condition.

While the applications and benefits of BIM for designers seem quite obvious, BIM can also act as an effective information management system for the precast concrete manufacturers producing prefabricated structural elements. Component specific information can be stored into the BIM and the information can be communicated or integrated with other stakeholders (Hradil et al., 2014; Mostafa et al., 2020). For instance, the concept of BIM object library for precast element manufacturers has been proposed by many researchers (Huang & Krawczyk, 2007; Dave et al., 2013). The idea of BIM object library is such that the customers can surf on the library to find precast elements that possess most suitable design and material attributes.

Interestingly, to enable reuse of existing precast components, the BIM object library could include not only the new but also reused concrete elements, so that any interested customers can choose to purchase the reused ones as well. Bertin et al. (2020) have attempted to address this issue by proposing that a large material bank should be created where the reusable components from existing buildings are stored; a database could store the structural properties of the reusable components from the material bank, and the database could be linked to BIM modelling software, allowing the engineers to design new buildings with reusable components.

The limitation of BIM, however, is that it might not be available for most of the existing buildings (Adamu et al., 2020). Nevertheless, with technological capabilities such as laser scanning, digital photography, data analytics, and machine learning, scan-to-BIM and photogrammetry concepts can be employed to create BIM models of old buildings (Cheng & Ma, 2013; Volk et al., 2014; Adamu et al., 2020). It is important to acknowledge, nonetheless, that those BIM models are merely visual, and designers might have to manually add other component related information to the model.

Additionally, there is a lack of globally applicable BIM-based EoL frameworks or prototypes, as well as lack of standard way of information exchange (Akinade et al., 2017; Akbarieh et al., 2020). Legislators or policy makers at national and international arena are expected to resolve those issues in the future, thereby facilitating the BIM applications for component reuse. Also, on the technological side, for BIM to realize aforementioned potentials, Lu et al. (2017) assert that its information readiness and computational capabilities must be improved further in the future.

Internet of Things (IoT)

Furthermore, for the building components to be reused, it is critical that the customers need to be assured of their quality and functionality (Marzouk & Elmaraghy, 2021). This requires real-time identification and interrogation of the components, such as location, usage, performance, maintenance record, ownership, and other functional properties of the components (Geldermans, 2016; Xing et al., 2020). Also, when designing new buildings with reused components, collection of such information needs to be rather smooth and efficient (Kozminska, 2019). This further implies that the detailed lifecycle information of structural components needs to be tracked and updated (Iacovidou et al., 2018). The lifecycle information includes the components' service history as well as the changes to component's mechanical and material characteristics (Swift et al., 2017).

Bertin et al. (2019) assert that IoT can act as a crucial digital technology for monitoring and collecting the lifecycle information of the structural components, consequently enabling the component reuse. While the IoT involves wide range of technologies that enable networked connection of physical objects through internet (Ellen MacArthur Foundation, 2016), RFID technology is the particular focus in this study. The RFID technology has several attributes such as the ability to gather data; capacity to store information; ease-of-use; affordability and durability (Iacovidou et al., 2021). Additionally, RFID technology enables automatic identification (Ness et al., 2015), traceability (Swift et al., 2017), as well as real-time transmission of information to and from the components (Pagoropoulos et al., 2017; Adamu et al., 2020).

It is important to note that the structural components themselves are hardly capable of gathering, integrating and communicating data by themselves; Hence, RFID tags are required to be attached to the components for such functionalities. Several researchers have already recognized RFID as a significant tool for tracking, gathering, updating, and sharing the lifecycle information of structural components (Schultmann & Gollenbeck, 2010; Valero et al., 2015; Iacovidou et al., 2018; Adamu et al., 2010). Among others, an important use of the RFID or sensors-provided data is tracking of the structural components for effective logistics and inventory management (Wang et al., 2018; Sarkar et al., 2022).

A RFID tag comprises a tiny radio antenna that conveys data to an RFID tag reader over a limited distance. For distinguishability, each RFID tag has a unique electronic product code (EPC) assigned to it. Basically, there are two types of RFID tags – active and passive. The active RFIDs have inbuilt mechanism to power it through batteries or an external energy source. On the contrary, the passive RFIDs use the electromagnetic field of RFID readers to draw energy. Usually, the active RFIDs operate at ultra-high frequency (UHF), and the passive RFIDs operate at low, high, or ultra-high frequency. Whereas the active RFIDs have better capabilities in terms of storage capacity and reading distance, they are rather expensive and have shorter lifespan in comparison to the passive RFIDs (Ness et la., 2015).

While sensors could also be incorporated into structural components separately, Ness et al. (2015) suggest that sensors for measuring physical characteristics such as temperature, pressure, or hazardous chemicals can be embedded as additional features of RFID tags themselves. For instance, Zhang et al. (2016) have demonstrated the applicability of passive high-frequency RFID sensors in detecting corrosion of structural components. Moreover, Zhang and Bai (2015) demonstrated a mechanism with RFID strain sensor that can measure deformation of structural components and can transfer the information to BIM. These information regarding the change or potential change in quality and performance of the structural components are critical for carrying out predictive maintenance, thereby extending the component's life and reusability (Riaz et al., 2014; Dave et al., 2018; Cheng et al., 2020; Dahanayake & Sumanarathna, 2022).

Motamedi and Hammad (2009) have proposed RFID as distributed BIM database, which is similar to data-to-tag approach described by Pais & Symonds (2011) and distributed ledger approach proposed by Minunno et al. (2018). They propose that RFID tags can be permanently attached to building components, and the tags can store a part of BIM information that are related to respective components. This way, all the value chain actors can access the lifecycle information of components in real time, without having to connect to a central database. While the limited memory storage capacity of the RFID tags could be a problem, data compression techniques can be employed to the RFID tags, enabling a larger data storage capability (Pais & Symonds, 2011; Swift et al., 2017). Figure 7 illustrates the interconnection of IoT, BIM and value chain actors.

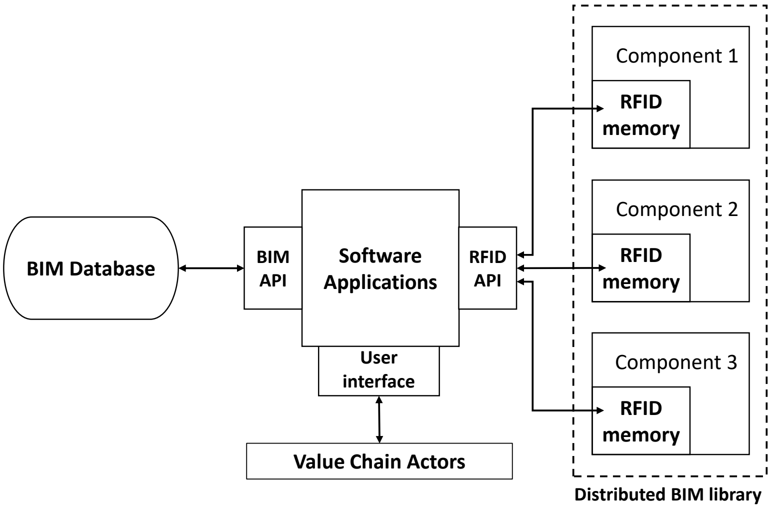

Figure 7. RFID, BIM and value chain actors' integration (Based on Motamedi & Hammad, 2009).

Ness et al. (2015) observe that despite the extensive studies on RFID and BIM, separately, their technological integration has not been studied enough. The need for integrating different digital technologies is further emphasized by Amadu et al. (2020). For instance, the lifecycle information gathered with RFIDs and sensors can be pooled and organized into BIM database, such that the information can be easily accessed and transferred throughout the construction value chain when necessary (Motamedi & Hammad, 2009; Lu et al., 2011; Vähä et al., 2013; Iacovidou & Purnell, 2016; Swift et al., 2017; Ness et al., 2019). However, for the seamless information analysis and transfer, BIM must employ standard data classification and segregation methods when retrieving data from the RFIDs (Swift et al., 2017). Additionally, an integrated cloud system can be used as the information storage and management platform (Xing et al., 2020).

Providing all value chain actors an unlimited access to the information stored in RFID tags can be a major hurdle for adoption of RFID tags as distributed BIM library; the major concerns are related to data privacy and security (Motamedi et al., 2011). To overcome this challenge, Motamedi et al. (2011) have developed, and proven through case study, a role-based access method that employs multi-level encryption and role-based access control policy (ACP). On the other hand, Bertin et al. (2019) proposes that the most essential BIM data can be stored into RFID chips as unmodifiable information. They argue that such an approach is necessary because the original BIM data might get lost or modified when ownership of structural components change across the value chain.

Interestingly, since the passive RFID chips are durable and highly resistant to harsh environments (Iacovidou et al., 2018), they can be submerged into the concrete already during the prefabrication of structural components (Bertin et al., 2019). Additionally, Zhang et al. (2016) suggest that the high frequency RFID tags are better suited for the built environment, because they have better performance in metal environment, in comparison to low frequency RFIDs. However, it is important to synchronize among the value chain actors, what sort of RFID tags and RFID readers are used; because the reading and writing of information through RFID can become problematic due to lack of common frequency level across different vendors (Ngai et al., 2008; Sharma et al., 2020).

Robotics

The adoption of robotics in the construction sector, particularly from the perspective of advancing circular economy, has been lagging, despite its potential to create value for the stakeholders (Chu et al., 2013; Pradhananga et al., 2021; Seyrfar et al., 2022). Delgado et al. (2019) observe that the challenges to adoption of robots, for component reuse practices, include the need for high capital investment, high complexity of the construction activities, lack of clear value capturing mechanism, and lack of integration among the value chain actors. Moreover, the unstructured nature of construction environments (Lublasser et al., 2017), stakeholders' resistance to change, fragmented supply chain, variability of building designs, and dissonant market factors also pose the challenges (Carra et al., 2018). Additionally, the complications to adoption are associated to human-robot interaction or collaboration, such as lack of skilled manpower (Lee et al., 2015) and safety concerns when human and robots have to operate in same workspace (Sarc et al., 2019).

In the past, researchers have focused on robot-assisted automating techniques for construction, leaving the automation techniques for deconstruction rarely researched (Lee et al., 2015). Consequently, robotics has mostly been recognized as an effective technology in upstream activities in the construction value chain, such as prefabrication, assembly and maintenance (Pan et al., 2018). Nevertheless, the potential implications of robotics for reuse of structural components cannot be ignored in the future (Bock & Linner, 2011; Kerin & Pham, 2019).

Through use of robotics, health and safety concerns related to manual labor could be reduced or even eliminated (Pan et al., 2018; Delgado et al., 2019). While a few researchers have already initiated exploration in this direction, there is still a need for further research. So far, there are two distinct potential applications of robotics for structural component reuse, that are recognized by studies, namely the deconstruction and component sorting.

First, the application of robotics for the deconstruction process can yield promising efficiency and effectiveness for reuse (Lee et al., 2015). As Lublasser et al. (2016) emphasize, since the component recovery process can be repetitious, labor intensive, and even unsafe, use of robotics is imperative. Pan et al. (2018) concur that with the help of robotics enabled automated deconstruction, existing buildings can be approached as material banks.

The feasibility of robot supported deconstruction has already been substantiated in a study by Lublasser et al. (2016). Lee et al. (2015) also observed that Japan has already been successfully employing single-task construction robots (STCRs) and semi-automated on-site factories for the deconstruction of buildings. Interestingly, Cruz-Ramirez et al. (2008) demonstrated use of robots to unfasten nuts and bolts from steel-ceiling structures. The authors employed vision system that uses multi-template matching and multi-frame integration techniques to effectively locate and undo the screws. The use of robots for unfastening screws and bolts from structural components has been further refined by other researchers (Biggs et al., 2011; Huang et al., 2019a; Yildiz & Wörgötter, 2019; Li et al., 2020; Zhou et al., 2022).

In the future, Carra et al. (2018) emphasize that, the effectiveness of robotics can be further enhanced through integration to data collection and sharing technologies such as Augmented reality, Virtual reality, IoT, and BIM. For instance, Lee et al. (2015) suggest that the disassembly sequence with STCRs can be based on the BIM data. If the existing buildings have only 2D data instead of CAD or BIM data, they propose that the 2D data can be translated to BIM and subsequently used for STCR assisted disassembly process. Similarly, Lundeen et al. (2019), as well as Carra et al. (2018), argue that the robots can leverage the data from RFIDs, sensors and BIM to autonomously adapt to unstructured work environments. A similar finding was also proposed by Yagi et al. (2005) that robots can acquire information from the components embedded RFID tags, and the retrieved information can guide the robot to accomplish component specific tasks. The simple mechanism of robot assisted disassembly is illustrated in Figure 8.

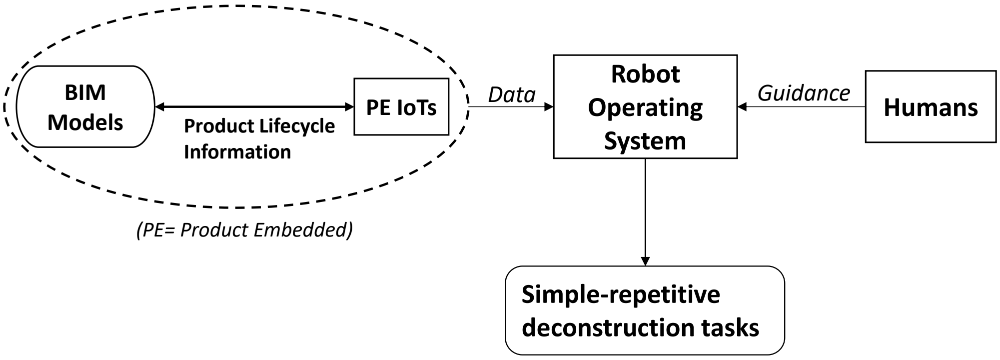

Figure 8. Mechanisms for robot assisted disassembly.

Second, Wilts et al. (2021) propose that robotic sorting systems, based on artificial intelligence, can be used to identify and segregate the reusable components from non-reusable ones. In their study, Laskurain-Iturbe et al. (2021) also recognize the applicability of robotics in material or component segregation. Lublasser et al. (2017) further emphasize the significance of automated robotic systems for separating hazardous materials from the reusable components. However, there are hardly any recorded evidence that the robotic systems are used to sort large structural components such as beams, columns, and slabs. It is imperative that further studies are required in this direction.

2.3 Reuse as a CE Practice in Manufacturing Industry

In a narrow sense, circular economy practices strive to promote environmental sustainability by effectively and efficiently exploiting the residual value of a products that have outlived their usefulness. Among different circular economy principles, reuse is considered a key dimension of circular economy, that is also economically and environmentally more beneficial than recycling (Kalverkamp & Raabe, 2017; Garrido-Hidalgo et al., 2020). By reusing a product or its components, consumption of virgin natural resources and energy can be avoided, that would have otherwise been used to produce similar product or components. Moreover, since many of the end-of-life products still possess well-functioning components, the economic benefits can be reaped by exploiting the residual value embedded into them.

2.3.1 Components Reuse: Remanufacturing

Reuse of a whole product is not always a possibility, for a simple reason that the product reaches end-of-life stage when it can no longer fulfill its original purpose. In such a case, if the product is not to be recycled or disposed as waste, either the product should be repurposed, or the reusable components of the product should be recovered and restored to its previous functionality and performance. The latter is generally known as the remanufacturing (Aziz et al., 2021). A general process of remanufacturing is illustrated in Figure 9.

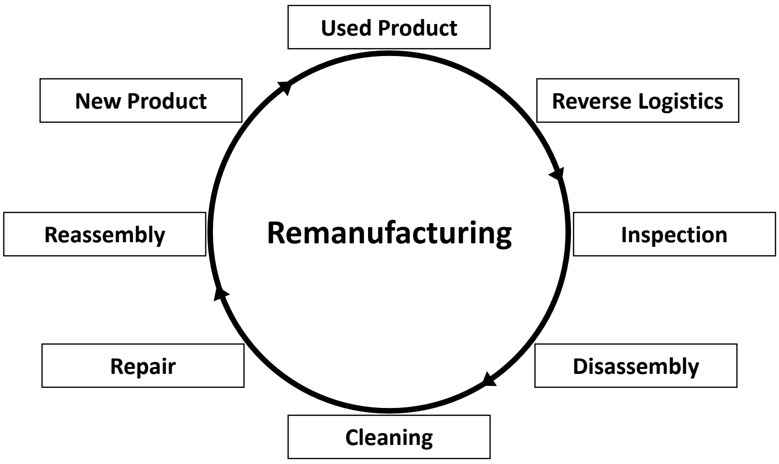

Figure 9. Remanufacturing process.

In manufacturing industry, it is imperative that a distinction need to be made between the terms reuse and remanufacturing, though they are often used interchangeably. Whereas reuse implies reusing the whole product, remanufacturing implies reusing the components to create a new or new-like product. For instance, Lund (1984) defines remanufacturing as “restoration of used products to a like-new condition, providing them with performance characteristics and durability at least as good as those of the original product. Through a series of industrial processes, worn-out or discarded products are completely disassembled, their useable component parts are cleaned and refurbished, new parts are provided where necessary, and the parts are reassembled and tested to produce units meeting new product performance standards”. Generally, as shown in figure below, a remanufacturing process involves multiple sub-processes - disassembly, cleaning, inspection, repair, replace and reassembly (Hatcher et al., 2011; Matsumoto et al., 2016).

Since the remanufactured products are often lower priced, they can promote the social welfare among low-income societies or economies (Matsumoto et al., 2016). However, in order to ensure that remanufactured products are lower priced than their new counterparts, it is important to avoid all potential extra expenses (Wang et al., 2019). For instance, Wang et al. (2017) argue that it is critical for companies to maintain optimal component reuse volume, because both excess and insufficient volume can jeopardize the economic benefits through unnecessary expenses. Smith et al. (2016) stress that complete disassembling of a product might not be feasible economically and technically, hence, selective disassembly should be opted. Additionally, for remanufacturing to be economically and operationally viable, companies need to overcome several other challenges.

2.3.2 Challenges to Components to Reuse

From operations management point of view, remanufacturing is more complex than the traditional manufacturing (Matsumoto et al., 2016). Remanufacturing consists of three basic processes – sourcing the used products or components (reverse logistics), actual remanufacturing (disassembly to reassembly), and sales of remanufactured products. Each of these processes are subject numerous challenges (Teixeira et al., 2022).

One of the fundamental challenges of remanufacturing is the reverse logistics or reverse supply chain (Kalverkamp & Raabe, 2017; Garrido-Hidalgo et al., 2020). It is often argued in the literatures that reverse logistics can be a costly endeavor for the companies. Nevertheless, if disposal costs and waste taxes increase in the future, the relative costs of reverse logistics might become low. Additionally, the salvage value of take-back products, after remanufacturing, could compensate the reverse logistics costs (Klausner & Hendrickson, 2000).

Further, since the remanufacturing is not yet mainstream in manufacturing industry, companies often lack the proper mechanism or channel for reverse logistics. While the manufacturers can establish themselves an effective mechanism for reverse logistics, such as closed-loop supply chain (MahmoumGonbadi et al., 2021), another way to overcome the challenge is to collaborate with third parties that can provide the reverse logistics services (Nasr & Thurston, 2006). Additionally, Nasr & Thurston (2006) argue that reverse logistics becomes a less prominent challenge if the manufacturers have adopted product-service system (PSS) as revenue models. With PSS, the manufacturers retain the ownership of the products, and hence possess a greater control over the residual value of the products when they reach end-of-life. In addition to greater ease in collecting the used products, PSS could also improve the customer acceptance of the remanufactured products (Mangun & Thurston, 2002; Matsumoto et al., 2016). However, manufacturers might still be hesitant to invest in reverse-logistics mechanism and other remanufacturing technology, because of perceived ambiguity regarding the return-on-investment (Raj et al., 2020; Teixeira et al., 2022).

Additionally, inventory management of recovered components as well as remanufactured components could be a challenge in remanufacturing because the inventory holding and management costs can impact the economic viability (Guide, 2000; Matsumoto et al., 2016). It is also worth acknowledging that the markets for the remanufactured products are still at infancy (Matsumoto et al., 2016). Therefore, manufacturers must have effective strategies to deal with customers' durability and reliability concerns regarding the remanufactured products.

Another important thing to consider when gathering and holding inventory of recovered components is that the components do not become obsolete in the market. For the remanufacturing to be viable, the level of technological innovation associated to the product should be rather stable (Guide, 2000; Hatcher et al., 2011); If not, there is a risk that new technological innovations can turn the current technology obsolete, thereby reducing market competitiveness of the remanufactured products. Consequently, instead of capitalizing on the resale value of components, companies might even need to allocate further resources for their disposal.

Next, remanufacturing challenge can also stem from the lack of information on product lifecycle as well as the perceived risks or ambiguity on the quality of recovered components (Winans et al., 2017). de Sousa Jabbour et al. (2018) concur that the implementation of CE principles faces mostly the challenges related to lack of product lifecycle information and the uncertainties associated to costs, returns, and technology adoption timeline. Other researchers have also stressed that there is a level of uncertainty regarding the quality, quantity, and timing of returned products (Ondemir & Gupta, 2014; Wang et al., 2019; Teixeira et al., 2022).

Often, when product is sold by the manufacturer, the product lifecycle data stream is broken, particularly because of the lack of standard methodology or system for subsequent customers to update the product status (Wang & Wang, 2019). Such lack of product or component traceability is even more prevalent for the products that were designed in the past, because they were rarely designed with remanufacturing in mind (Tam et al., 2019).

Disassemblability of products is another challenge in remanufacturing that require careful consideration from product designers (Wang et al., 2019). Products with large number of parts and complex interconnections are often difficult to disassemble and could be time and resource consuming (Smith et al., 2016; Joshi & Gupta, 2019). For instance, researchers emphasize that remanufacturing of consumer products, particularly the complex ones such as electronics, is the more challenging compared to simpler products (Matsumoto et al., 2016; Tam et al., 2019).

Finally, the product designs can also become a challenge in remanufacturing because the conventional product designers and manufacturing engineers often lack the necessary knowledge and technical guidelines to adopt design-for-reuse philosophy in early product designs (Guide, 2000; Matsumoto et al., 2016; Aziz et al., 2021). Additionally, if the manufacturers themselves are not involved in remanufacturing, they often inhibit remanufacturability of their products because they consider that third party remanufacturers might cannibalize their sales through direct competition (Hatcher et al., 2011).

While firms can use different digital technologies to gather product and component related information, they need to invest on standard data processing and management systems that are capable of turning the information into valuable insights (Ingemarsdotter et al., 2020). Moreover, since the value chain actors are often independent business entities, conflict of interest might arise between the parties (Kalverkamp & Raabe, 2017). The actors might be hesitant to share product related information due to data privacy and security concerns, for instance (Motamedi et al., 2011). Finally, the demand for remanufactured products is still very low, due to customers' negative perception or lack of understanding regarding the quality of such products (Yang et al., 2018).

2.3.3 Digital Tools for Components Reuse

Digitalization is considered as one of the key enablers of circular economy practices (Ellen MacArthur Foundation, 2017). According to Liu et al. (2022), digital technologies can enable the whole remanufacturing process, starting from the identification and disassembly of reusable components to rebuilding new or new-like products. For instance, industry 4.0 technologies can play critical role in tracking the in-use and post-use information of products to identify and recover reusable components. As Blömeke et al. (2020) assert, component reuse practices in the manufacturing can be enabled with the use of IoT, cyber-physical systems, and cloud manufacturing that further employ other technologies such as RFIDs, sensors, barcodes, digital twin, VR, and AR. Moreover, potential use of robotics, as facilitator of component reuse practices, has also been emphasized by the researchers (Sarc et al., 2019; Aziz et al., 2021; Teixeira et al., 2022). Some of key literatures selected for this study are presented in table below.

Table 2. Synthesis of relevant literatures discussing the role of digital technologies (DTs) in remanufacturing.

Author	**Research Type/Context/Setting**	**Reuse Aspect Addressed**	**DTs**	**Relevant Key Ideas/Findings/Propositions**
Digital twin focused				
Wang & Wang, 2019	Prototype development for WEEE	*DfDR, Remanufacturing planning*	Digital twin, IoT	Framework for digital twin as an information repository for a product throughout the product lifecycle, which in turn allows assessment of quality, performance, and reusability of the product at EoL
Adisorn et al., 2021	Literature review, Expert discussion and workshop	*Product lifecycle traceability, Remanufacturing planning*	Digital product passport (DPP), RFID	Digital twin can act as information repository for a product throughout the product lifecycle. It is important to define what information are critical for product circularity and how the information sharing can be managed while protecting stakeholder confidentiality
Walden et al., 2021	Case study, Concept development	*Product lifecycle traceability, Remanufacturing planning*	DPP	DPP can act as shared information repository for all value chain actors. Essential product lifecycle information can be recorded in DPPs and they can be used for lifecycle assessment
IoT focused				
Jun et al., 2009	Concept development	*Product lifecycle traceability, DfDR, Remanufacturing planning*	RFID, sensor	Framework for RFID application in product lifecycle management. Products as product embedded information device (PEID) could enable easier storage, update, and transfer of product lifecycle information across different stakeholders. At end of life, the information can be assessed for reverse logistics, inventory management, reusability diagnosis, disassembly planning, remanufacture planning, and design optimization.
Fang et al., 2015	Concept development	*Product lifecycle traceability, DfDR, Remanufacturing planning*	RFID, Sensor	Smart sensors and RFIDs can be embedded into products so that product lifecycle information can be gathered and stored. The sensor-provided data can be used to optimize different operations in product remanufacturing process and also to optimize future product designs
Mashhadi & Behdad, 2017	Concept development, Case study of hard disk drives	*Product lifecycle traceability, remanufacturing planning*	RFID, Sensor	Sensor-provided lifecycle data can be used to assess the quality and reusability of products. Based on their reusability index, recovered products can be categorized into different clusters, where each cluster has a distinct EoL decisions and scheduling priority.

Bressanelli et al., 2018	Literature review, Case study in household appliance industry	*Product lifecycle traceability, DfDR, Remanufacturing planning*	IoT, Big data analytics	IoT, along with dig data analytics, can enable several CE activities, such as predictive maintenance, product tracking & monitoring, design optimization, quality assessment, and remanufacturing decision making.
Alqahtani et al., 2019	Literature review, Concept development	*Warranty cost management of remanufactured products*	RFID, Sensor	Sensor-provided data, from sensor embedded product, can be used to determine the most optimal warranty policy and warranty period when the product is remanufactured. Sensor can be embedded into the remanufactured product to monitor its quality and performance, so that warranty claims are reduced and effective preventive maintenance is carried out on time.
Ingemarsdotter et al., 2020	Semi-structured interview, case study in LED lighting industry	*Product lifecycle traceability, DfDR, Remanufacturing planning*	IoT	IoT can support servitization, tracking and recording in-use and post-use information, conditions monitoring, predictive maintenance, lifetime estimation, and restorative designs. The challenges to IoT adoption are lack of standard data management systems and difficulty designing the IoT enabled products.
Robotics focused				
Wegener et al., 2015	Concept development	*Robot assisted disassembly*	Robotics, Image processing	Framework for use of collaborative robots in Disassembly of Electric vehicle (EV) batteries. Whereas humans could carry out more complex tasks, the robots could perform simpler repetitive tasks such as unfastening of screws and bolts. To adapt the robot to work with batteries of different shapes and sizes, either human could guide the robot or the robot could use image processing technology. In case of the latter, further research is required.
Huang et al., 2019b	Concept development, Applied case study (water pump disassembly)	*Robot assisted disassembly*	Robotics, Sensor	Framework for human-robot collaboration (HRC) in disassembly of products. HRC disassembly can become flexible or adaptable to products of different sizes and design, through the use of compliance control in the collaborative robots.
Blömeke et al., 2020	Literature review, Case study	*Robot assisted disassembly, Remanufacturing planning*	Robotics, I 4.0 technologies	Among others, collaborative robots could semi-automate disassembly of products and other repetitive remanufacturing activities. Use of collaborative robots and I 4.0 technologies in remanufacturing could improve remanufacturing productivity and quality of remanufactured products.
Xu et al., 2020	Concept development, Applied case study (simplified computer disassembly)	*Robot assisted disassembly*	Robotics	Framework for disassembly sequence planning (DSP), for HRC, can be formulated using modified discrete bees algorithm based on Pareto (MDBA-Pareto). HRC can be cost-efficient and effective for product disassembly that constitutes series of tasks with different levels of cost, time and difficulty.

Digital Twin

Digital twin is defined as “evolving digital profile of the historical and current behavior of a physical object or process that helps optimize business performance. The digital twin is based on massive, cumulative, real-time, real-world data measurements across an array of dimensions” (Parrott & Warshaw, 2018). It is not a completely new concept, rather it is often interchangeably used with other concepts such as digital product passports (DPP), environmental product declaration (EPD) and material passport (MP) (de Sousa Jabbour et al., 2018; Walden et al., 2021).

In the automobiles industry, the alternative concept to digital twin is international material data system (IMDS), wherein “all materials present in finished automobile manufacturing are collected, maintained, analyzed and archived” (DXC Technology, 2021). Similarly, in the construction industry, building information model (BIM) is used as a common alternative to digital twin. In the same way that IMDS was developed to address the 3R needs of end-of-life vehicles as mandated by End-of-life Vehicle Directive (2000), lately the BIM is being recognized for it’s potential to facilitate component reuse in construction industry. In the manufacturing industry, digital twin concepts are also getting recognized for the similar potential.

As the definition suggests, digital twin is a digital representation of a product that has not only the geometrical or 3 dimensional attributes of the product but also varieties of product related information that are systematically stored (Chen & Huang, 2021). Because the physical product could be accompanied by a digital twin throughout its life cycle, it enables different stakeholders to interact with product information at various levels in the supply chain, thereby enabling the product traceability (Walden et al., 2021).

The traditional approach to product data management is somehow limited to manufacturer’s in-house operations (Chen & Huang, 2021). Usually, the information related to the products are gathered and analyzed until the product ownership are handed over to the customers. This would imply that when the product reaches end-of-life and collected back by remanufacturer, there is lack of complete information related to physical and non-physical changes (e.g., maintenance, ownership, location) along the product lifecycle (Wang & Wang, 2019). Digital twin could overcome this information gap by recording the product related information throughout its lifecycle (Adisorn et al., 2021). This application of digital twin as lifecycle-information repository is illustrated in Figure 10.

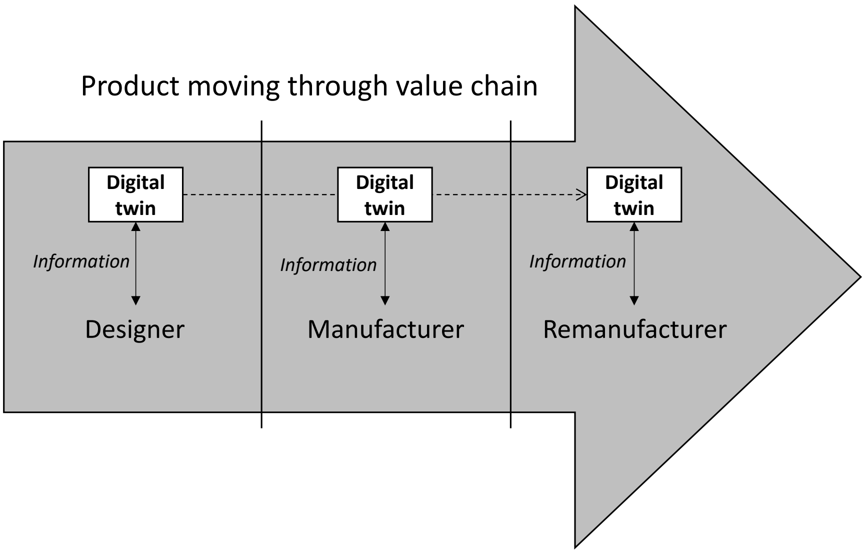

Figure 10. Digital twin for storing & sharing lifecycle information across value chain.

The definition of digital product passport (DPP) by European commission (2013) also incorporates the notion that digital twin could provide essential information for component reuse. Wherein, DPP is defined as “a set of information about the components and materials that a product contains, and how they can be disassembled and recycled at the end of the product's useful life”. However, for remanufacturing to be effective and efficient, other historical or updatable product information are also required, such as location, usage, performance, maintenance record, ownership, and changes to functional properties (Geldermans, 2016; Xing et al., 2020). Moreover, as Walden et al. (2021) emphasize, for a component to be reused, associated lifecycle energy and emissions also need to be assessed. Such data or information can be pooled into and shared through the digital twin. Wang & Wang (2019) concur that the digital twin can act as a bridge between the cyber world and the physical world (accompanied by IoTs). Nevertheless, for this to happen, information-sharing capability of digital twin need to be developed further into a cross-enterprise data-integration platform based on database technology (Chen & Huang, 2021).

Similar to BIM, there is no standard approach to the use of digital twin in the manufacturing industry (Walden et al., 2021). While the manufacturers could provide the digital twin of the product to subsequent actors in the value chain, when delivering the products, there is a concern related to the confidentiality of business secrets and IPR securities (Wang & Wang, 2019; Walden et al. ,2021). Further research is necessary how this challenge can be resolved in the future (Chen & Huang, 2021).

IoT

IoT is considered as one of the critical technologies for enabling remanufacturing by several researchers (de Sousa Jabbour et al., 2018; Cwiklicki & Wojnarowska, 2020; Kristoffersen et al., 2020). For the remanufacturing to be feasible, products or components need to be returned back to the original manufacturers or external remanufacturing facilities. Moreover, the usability of the components need to be determined before investing time and resources in the remanufacturing process (Blömeke et al., 2020). Additionally, from the production planning and control perspective, the traceability of the products or components is critical for eliminating the uncertainties related to their quality, quantity and logistics (Guide, 2000; Tam et al., 2019). In this regard, IoT can play a significant role in remanufacturing by tracking, monitoring and recording the production, in-use, and post-use information of the products and components (Bressanelli et al., 2018; Ingemarsdotter et al., 2020).

IoT implies the interconnectivity of physical objects or systems through internet, for the collection, storage, and distribution of data. Not all of physical objects are capable of sensing, storing and transmitting of information; therefore, to enable those attributes, often RFID tags and sensors are attached to the physical objects (Jun et al., 2009). In this study, however, RFID is the particular focus, and there are a few reasons for this. First, while the QR codes are barcodes are enough to track the products or components, RFID tags are preferrable because they have higher data storage capacity, automation potential, information editability, and resistance to harsh environment (Luttropp & Johansson, 2010; Gligoric et al., 2019; Raza, 2022). Second, instead of embedding products with separate sensors and RFIDs, RFIDs can incorporate sensor technology themselves (Jun et al., 2010).

RFID tags can be attached to the products or individual components so that the information related to the product or component can be both stored and retrieved throughout the value chain (Minunno et al., 2018; Wang & Wang, 2019; Arrido-Hidalgo et al., 2020; Mboli et al., 2022). Jun et al. (2010) have developed a complete framework in this direction, describing how RFID technology could be utilized for product lifecycle management, including logistics management, inventory management, predictive maintenance, and design optimization.

When the product is manufactured, the embedded RFID tags could accommodate information, such as product model, product design, materials used, manufacturing date, warranty terms, maintenance instructions, and disassembly guidelines (Luttropp & Johansson, 2010; Ondemir & Gupta, 2014). This approach of storing essential product information into RFIDs have been emphasized by several researchers, for example the concepts of data-to-tag (Pais & Symonds, 2011; Motamedi et al., 2011), product passport (Gligoric et al., 2019), and distributed ledger (Minunno et al., 2018). Such information embedded into tags at the beginning-of-life often remains static throughout the product's lifecycle and gets changed when the product is remanufactured for second life (Fang et al., 2015).

When the product leaves the manufacturing facility and moves through value chain, the tags could be used for real-time tracking and monitoring of lifecycle information of the product (Alqahtani et al., 2019; Liu et al., 2022). The embedded RFIDs enable the collection and sharing of the historical data related to product usage, use conditions, maintenance, as well as the changes in ownership, location and material characteristics (Ondemir & Gupta, 2014). Interestingly, the data from RFID tags can be transferred to the product's digital twin, where the information can be stored and accessed by different value chain actors (Chen & Huang, 2021; Zambrano et al., 2022); this is illustrated in Figure 11.

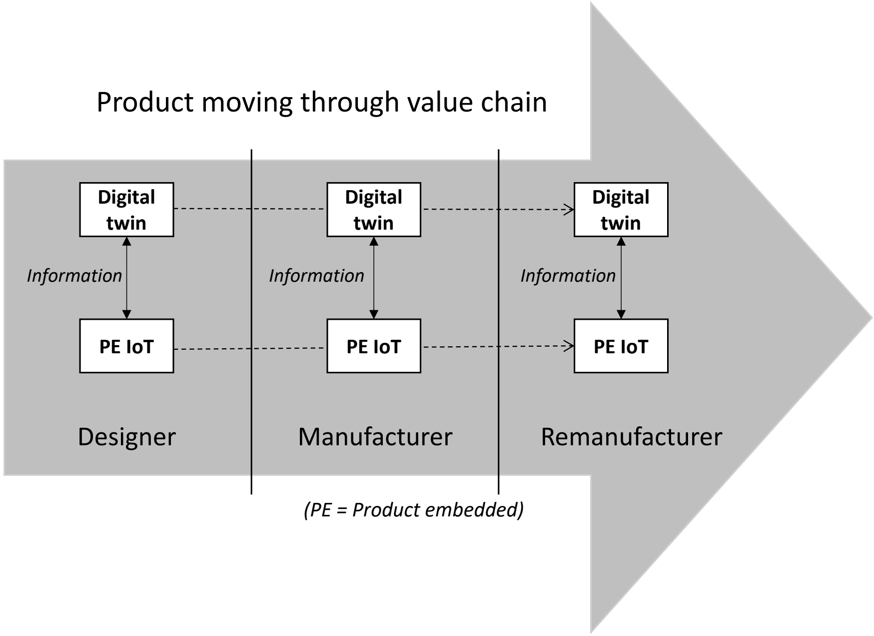

Figure 11. IoT for gathering & sharing lifecycle information across value chain.

Next, when the product is returned to the remanufacturer, with the help of data analytics the retrieved data from RFIDs could be used to estimate the disassembality, quality, and remaining lifetime of components (Ondemir & Gupta, 2014; Bressanelli et al., 2018; Ingemarsdotter et al., 2020), which are essential for ensuring the reliability of the remanufactured products (Alqahtani et al., 2019). Additionally, if RFID tags store information such as maintenance history, cleaning efficiency, product failures, upgrading challenges, and disassembly efficiency, the information could be utilized by the product designers to optimize reusability of the next generation of products (Fang et al., 2015; Yang et al., 2018; Joshi & Gupta, 2019).

Since inventory management is an inevitable part of remanufacturing process, RFID technology could be used for effective component tracking and monitoring (Liukkonen, 2015). In addition to inventory control, the data from RFIDs could also enable optimized scheduling and production planning for remanufacturing activities (Mashhadi & Behdad, 2017; Teixeira et al., 2022). Additionally, one of the critical contributions of RFID, among other IoT technologies, is that it enables PSS or servitized business models, allowing manufacturers to have a better visibility and control over the performance of both new and remanufactured products (Alcayaga et al., 2019; Ingemarsdotter et al., 2020). This is essential from reverse-logistics, predictive maintenance and future design optimization point of views. Alqahtani et al. (2019) proposed that the RFID tags could accompany remanufactured products when they are sold for second life use. Consequently, the remanufacturer can monitor second lifecycle information of the remanufactured products and carry out preventive or predictive maintenance, so that the warranty costs are reduced or eliminated.

However, for the purpose of storing large amount of information in the RFID tags, the limited data storage capacity of tags could pose a problem (Wang & Wang, 2019). While the ultra-high frequency tags and active tags have higher storage capacity (Ondemir & gupta, 2014), they tend to be rather expensive. Moreover, since there is not a standard frequency level for RFID tags across countries or even across vendors within a single country, reading and writing data might become problematic (Ngai et al., 2008; Jung & Lee, 2015; Sharma et al., 2020).

Robotics

The use of robotics automation for circular economy are yet to fully develop (Sarc et al., 2019; Liu et al., 2022). Nevertheless, research point out that robotics automation, often assisted by other digital technolgoies, can carry out component recovery process rather effectively (Ramirez et al., 2020; Liu et al., 2022). Particularly for the activities that are repetitive and error prone, automated robotics can significantly improve the process efficiency and minimize defects (Blömeke et al., 2020; Laskurain-Iturbe et al., 2021).

Traditionally, the remanufacturing activities, such as product disassembly, have been labor and energy intensive; therefore, automating these processes could enhance efficiency as well the environmental sustainability (Xu et al., 2020; Aziz et al., 2021). Huang et al. (2019b) substantiate, through their water pump disassembly experiment, that the robots could in fact improve the productivity of those tasks. However, the product heterogeneity in terms of shape, size, mass and surface texture, by design or due to use conditions, limits the complete robotic automation in remanufacturing activities (Carrell et al., 2009; Bentaha et al., 2014; Sarc et al., 2019). Additionally, the completely autonomous industrial robots are considered to pose a safety risk when put in the same workspace as humans; and the need to create separate working space for robots could incur extra costs for the companies (Sarc et al., 2019).

Therefore, Teixeira et al. (2022) propose that collaborative robots could be utilized for semi-automatic disassembly and cleaning of components. A similar finding was proposed by Zheng et al. (2017) who developed a basic framework to program the robots for disassembly tasks. Using of Bee algorithm, Xu et al. (2020) proposed a way to develop disassembly sequence planner for collaborative robots, such that the time and cost of disassembly is minimal. Parsa and Saadat (2021) also developed disassembly sequence planner for the robots, but with genetic algorithm. For the disassembly sequence planning and robot assisted disassembly, several researchers have emphasized the use of product design and other information that can be retrieved from CAD or digital twin (Hartano et al., 2022; Poole et al., 2022; Prioli et al., 2022; Ye et al., 2022). This simple mechanism for robot assisted disassembly is illustrated in Figure 12.

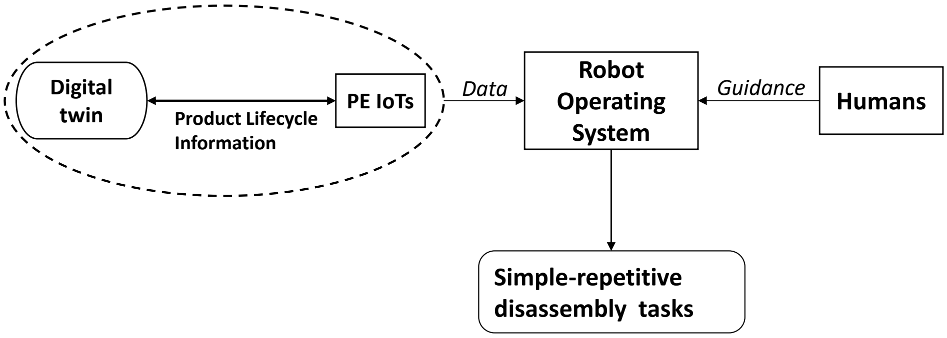

Figure 12. Mechanisms for robot assisted disassembly.

While studying robot assisted disassembly of electric vehicle batteries, Wegener et al (2015) propose that robots could be used for simpler and repetitive tasks such as removing the screws and bolts, whereas humans could carry out the complex tasks. Later, the application of robots for unfastening the screws and bolts for other products has been studied and refined by several researchers (Bdiwi et al., 2016; DiFilippo & Jouaneh, 2019; Yildiz & Wörgötter, 2019; Li et al., 2020; Zhou et al., 2022).

Unfortunately, despite huge potential of robotics for facilitating sustainable manufacturing and remanufacturing (Belhadj et al., 2022), there is still a scarcity of in-depth studies in this direction (Kerin & Pham, 2019; Enyoghasi & Badurdeen, 2021). The studies published so far also lack the convergence and, that needs to be resolved in the future studies (Poschmann et al., 2020).

2.4 Value Chain Actors and Their Roles in Component Reuse

As Trevisan et al. (2021) elegantly put it, the circular initiatives extend beyond the boundaries of a firm. In other words, transition to circular economy from the traditional linear economic model is a systemic change that cannot be accomplished with disparate efforts. Rather, it requires integrative and collaborative approach throughout the value chain and sometimes beyond (Antikainen et al., 2018). As Govindan & Hasanagic (2018) emphasize, implementation of the circular economy principles is a shared responsibility of all the stakeholders, including government bodies and value chain actors. Structural component reuse, as one of the circular economy dimensions, is no exception. Different value chain actors are responsible for the integrative efforts to make it a reality (Geyer et al., 2002).

For instance, when it comes to driving the reuse practices, customers are the key stakeholders in the entire value chain (Govindan & Hasanagic, 2018). As Gorgolewski (2008) emphasizes, the willingness of customers to accept reused products, or the products with reused components, is pivotal for implementation of reuse practices. This is the case because without demand from customers, sellers are not able to generate returns and therefore sustain their businesses, no matter how good the intentions are. For the customers themselves, the most critical thing about the products with reused components is the product’s warranty and the capability to address their needs and desires (Gharfalkar et al., 2016). Unless those criteria are fulfilled, they will not invest into the products (Hradil et al., 2014). Therefore, when selling products with reused components, both in construction and manufacturing, value chain actors need to make sure the products possess high level of quality, functionality, and performance.

In manufacturing sectors, manufacturers play a vital role in advancing the component reuse practices. Though, manufacturers often fear that remanufacturing may cannibalize their existing market share, fear of such cannibalization would become irrelevant if the manufacturers themselves are involved in remanufacturing (Gharfalkar et al., 2016). Rather, they would potentially improve the profitability while also contributing to environmental wellbeing of the planet. However, how the manufacturers design their product is an important aspect for remanufacturing because the designs can significantly affect the product reusability and cost-efficiency of reuse practices.

Several researchers emphasize that the product designers should strive for design-for-disassembly (DfD) and design-for-reuse (DfR) approaches (Matsumoto et al., 2016; Cai & Waldmann, 2019; Franco, 2019). The designs should facilitate future disassembly of components with a level of ease (Sundin & Bras, 2005; Go et al., 2012) and without any potential damage (Forghani et al. 2021). Furthermore, the goals of such designs should be to enable multiple life cycles for the components (Bocken et al., 2016; Mestre & Cooper, 2017). As Nasr & Thurston (2006) emphasize, it is critical to assess technical and economic feasibility of component reuse already during the product development and manufacturing engineering stage. While they concur to the aforementioned notions that the product designs should consider the issues related to disassembly and durability, they add that the products should have embedded mechanisms to monitor usage and use conditions throughout the product lifecycle.

Product or component designers play the most significant role for component reuse because their design, documentation, and instructions are invaluable in the component disassembly and recovery process (Hradil et al., 2014; Tam et al., 2019). As Desai & Mital (2005) emphasize, the feasibility of remanufacturing is mainly driven by the product design rather than the disassembly process optimization. Joshi & Gupta (2019) concur that designers can impact the remanufacturing cost by influencing disassemblability of products, that is, the more difficult a product is to disassemble, the more costs will it’s remanufacturing incur.

One of the ways designers can enhance feasibility of component reuse is to use common components across different products in a product family. In addition to the ease of disassembly, this will allow the remanufacturers to mitigate supply uncertainty in terms of volume variability of returned components (Wang et al., 2019). Moreover, Sundin & Bras (2005) proposed that designers should design component hardware in a way that they can be modernized or upgraded, just in case the previous technology tend to become obsolete.

In the construction sector, similar to manufacturing, designers play a significant role in the structural component reuse because their design, documentation, and instructions play a significant role in component disassembly process and overall reusability of the components (Hradil et al., 2014). However, unlike manufacturing sector, in the construction industry the constructors barely design the buildings themselves. Rather, responsibility for building design are carried out by designers who are often separate entities in the construction value chain and, prefabricated structural elements are often designed by precast manufacturers who are also separate from the constructors. Nevertheless, the effectiveness and efficiency of structural component reuse is significantly affected by their design attributes (Smith & Hung, 2015).

Fivet (2019) emphasizes that the design of building components should foster open-ended reusability because the next life cycle requirements of the structural components cannot be foreseen. He proposes 5 essential design characteristics for this, namely the durability, versatility, modularity, reversibility, and adaptability. Further, the designs should incorporate attributes such as, among others, use of nut-and bolt connections rather than welding; use of components that can be assembled or disassembled with common equipment; and assigned liftings points on components for convenient component handling (Gorgolewski et al., 2008; Forghani et al., 2021). Moreover, for the time, cost and labor efficiency as well as the effectiveness of future deconstruction, Lee et al. (2015) suggest that designers should employ robot-oriented design (ROD). They propose that the building designs should take into account the compatibility of building components with robotic applications and the ease of robot access into component interconnections.

Unlike traditional design methods, which require building designers to create a design before procuring components, the reuse of old structural components in new buildings necessitates, first, checking component availability and properties, followed by an optimized design process to effectively utilize them (Addis, 2006; Bertin et al., 2019). For example, the design of new buildings should match the strength of the recovered structural components (Rakhshan et al., 2021); whereas the reverse would be true in conventional design process. Such departure from traditional design practice can be a challenge for the designers (Brutting et al., 2019), but it is important, nonetheless. As a result of the transition, designers must incorporate a high level of flexibility and adaptability into the design process (Gorgolewski, 2008).

Additionally, the demolition contractors, or disassembly workers- in case of manufacturing sectors, play an equally critical role for the structural component reuse. Unless the deconstructors or disassemblers are able to recover components intact, the components are not fit for second life use (Rios et al., 20159. Therefore, they need not only extra care but also appropriate tools and competent workers to recover undamaged components (Munroe et al., 2006). Moreover, before product disassembly and building deconstruction tasks could be executed, for the matter of efficiency and safety, disassembly sequence planning and other disassembly processes need to be outlined in detail (Sanchez, 2019). This planning process might require the disassembler to collaborate with other stakeholders, such as designers, manufacturers, constructors, and even independent engineering consultants.

As indicated, whereas companies act quite independently in open loop economy, at least in comparison, the closed loop or the circular economy require greater collaboration and collective decision making among several stakeholders (Kirchherr et al., 2018; Pinheiro et al., 2022). Therefore, understanding of multi-actor perspective is critical for the firms to implement circular economy practices (Rocha & Sattler, 2009; Awan et al., 2021). In a similar manner, component reuse involves a complex process of activities that directly or indirectly affect all the value chain actors. Hence, sharing of information and knowledge is a critical prerequisite to advance the component reuse practices (Hradil et al., 2014; Butzer, 2016). This implies that the understanding of different value chain actors' perspectives is crucial for advancing application of digital technologies for reuse, in both construction and manufacturing. This is also the goal of empirical study in this research.

2.5 Literature Synthesis

It can be fathomed from the literature review that despite several challenges, component reuse practices, in construction and manufacturing industry, could provide both economic and environmental benefits to the value chain actors. The literatures suggest that the major challenges to component reuse in construction and manufacturing are associated to lack of product or component traceability, lack of design attributes that support disassembly and reuse, and lack of market structures or mechanisms for the trade of reused components. Additional challenges of component reuse practices in the construction and manufacturing industries are lack of standards and stakeholders' reluctance in transitioning to component reuse practices. Nevertheless, to overcome the aforementioned challenges, and consequently, to make component reuse practices feasible, it is emphasized in the literatures that the capabilities of the selected digital technologies could be exploited.

First, BIM is, whereas, already known as an advanced tool for designing buildings and the components therein, designers can use it in the future to design structural components in a way that they can be disassembled and reused. It can also be used as a common source and repository of information across the value chain, thereby, improving the traceability of structural components. Consequently, when buildings reach end of life, deconstructors can access the static and historical information associated to the structural components, and an effective and efficient deconstruction plan can be formulated. Additionally, the BIM-provided information can be analyzed for quality measurements and lifecycle assessment of the recovered components before they are processed for second life use. Moreover, the BIM models of the recovered components can be transferred to a digital component library where designers can access the models and if suitable, incorporate them in new building designs.

Second, digital twin, similar to BIM, can be used for designing of products and components for disassembly and reuse. Also, since digital twin can be used as a lifecycle information repository across value chain, remanufacturers can access the information to assess how the quality and reusability of the components are. If the components are deemed reusable, the digital twin-provided information can be used for lifecycle assessment of the components as well as disassembly planning. However, unlike in the case of BIM, literatures do not discuss the use of digital twins (of reused components) in creating a digital component library.

Third, IoT devices, RFID tags or RFID sensors in particular, could be embedded into the components so that value chain actors can track and monitor the components throughout their lifecycle. This seems true both in the construction and manufacturing industries; though in the manufacturing industry, the devices might have to be embedded into the product instead of individual components. Nevertheless, the IoT devices can be used to monitor component’s historical information, such as changes in use conditions, performance, and quality, and relay that to corresponding BIM model or digital twin. The historical information can be used, among others, for predictive maintenance and optimizing the design of the components so that they are durable and reusable. Also, the IoT devices can be used as distributed ledger that stores the essential component information required for different value chain actors. Moreover, when components are recovered from the buildings or products, embedded IoT devices can be used for tracking the components for logistical and inventory management purposes.

Finally, robots are emphasized in the literatures for their ability to semi-automate the component disassembly process both in construction and manufacturing. For instance, literatures suggest that the collaborative robots can be used to carry out simple and repetitive tasks such as cleaning the components and unfastening the screws and bolts. However, due to technological limitations of the current robotic systems and the variability of components, use of robots in disassembly tasks still seem insubstantial.

Literatures reveal that the applications of the digital technologies in construction and manufacturing industries are more similar than different. Nevertheless, the difference is that the concepts of 'digital component library for reused components' and 'design with reused components' have not been discussed for the manufacturing industry. Additionally, the use of IoT-provided data for component design optimization has been rarely discussed in the construction industry.

Interestingly, in both industries, the digital technologies are closely linked to each other because of the complementary functionalities they possess. Whereas the BIM and digital twin can store component's design and other information, the IoT devices can track and monitor the components throughout their Lifecyle. Since IoT devices, such as RFID, possess limited memory capacity, they can store only the essential information; other historical information gathered by the devices need to be relayed to corresponding BIM or digital twin where the information is stored and updated. Further, the information can be used by collaborative robots for robot-assisted disassembly. Figures 13 and 14 depict the use of digital technologies by value chain actors, in construction and manufacturing respectively, for advancing the component reuse practices.

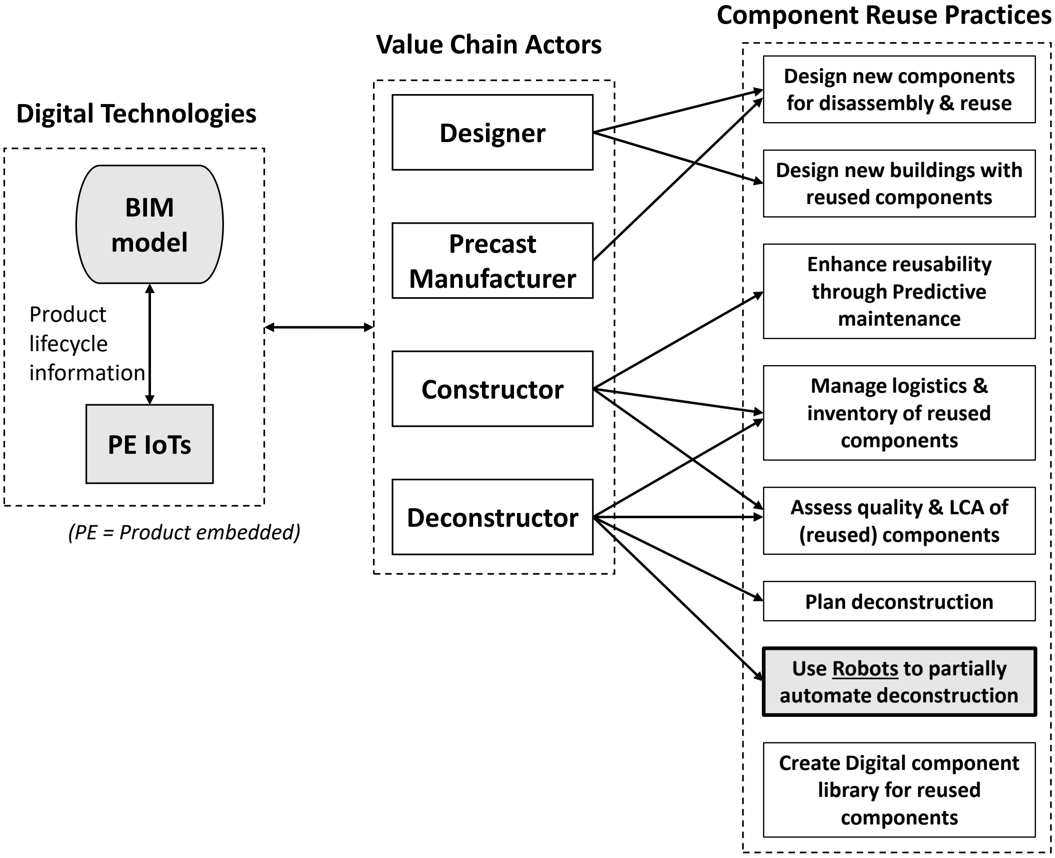

Figure 13. Applications of BIM, IoTs, and Robots for structural component reuse.

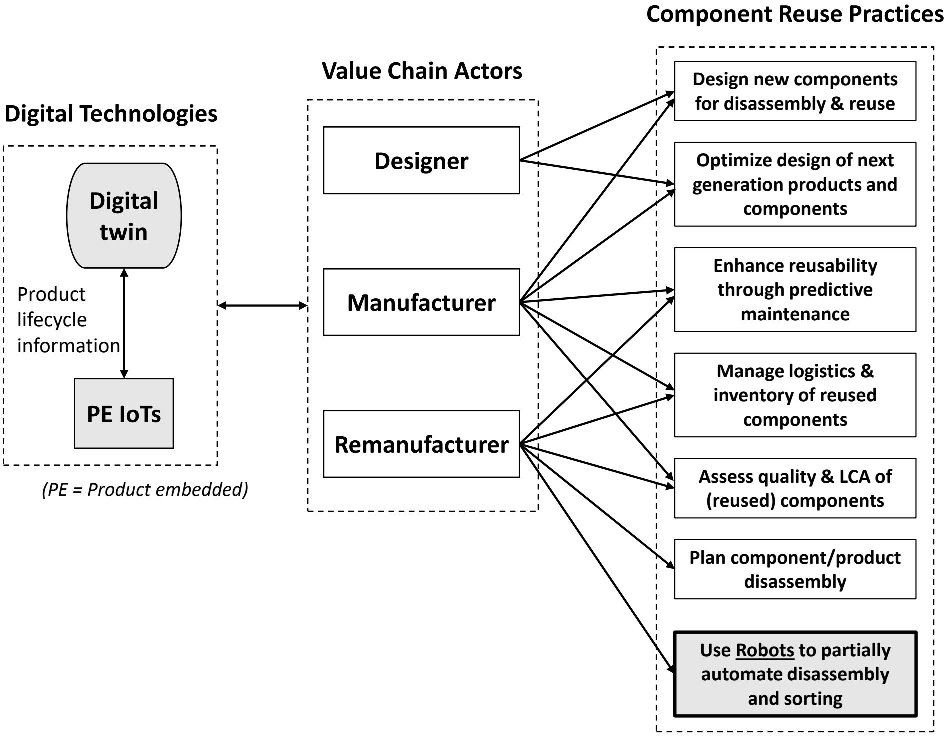

Figure 14. Applications of Digital twin, IoTs, and Robots for remanufacturing

While the digital technologies seem conducive to advance component reuse practices, it is not free of challenges and technological limitations. For instance, several researchers underscore the finding that companies are often hesitant to invest in the digital technologies because of high up-front costs and ambiguity regarding return on investment. Also, it is stressed that the increased level of information sharing among the value chain actors, fostered by digital technology, can pose serious information and data security issues. Moreover, it is also emphasized in several literatures that current digital technologies are not developed from the reuse point of view, and therefore, their functionalities and capabilities need to be developed further. For instance, both BIM and digital twin have limited capabilities when it comes to cross-enterprise information transfer and integration. This limits the level of collaboration among value chain actors, which is essential for component reuse.

Similarly, IoT devices are considered to lack standardization, which restricts the convenience of information sharing along the value chain. For example, if different components or products are embedded with RFID tags of different frequencies, then the actor who oversees handling the end-of-life components will also require RFID readers of different frequencies. Furthermore, current robotic systems hardly possess the flexibility to adapt and work with components of different shapes, sizes and quality, which limits the degree to which disassembly and post-disassembly activities could be automated.

3. RESEARCH METHODOLOGY

3.1 Research Design and Research Strategy

The research in this study aims to expand the understanding on how different digital technologies enable component reuse in construction and manufacturing sector. To address the objective effectively, the study incorporates the value chain perspective, i.e., perspectives of different value chain actors are gathered and analyzed. It is essential for this research design to take a pragmatic stance (Emmel, 2013) because extant literatures related to the research objective are rather fragmentary. Moreover, the use of digital technologies for component reuse, particularly in construction and manufacturing, are still at infancy; this implies the need for exploratory study on how different value chain actors have been using digital technologies for component reuse or how they think the technologies could be used in the future. Consequently, the research design for data collection and analysis is qualitative, and the method employed for this research is multiple case study.

The case study method helps in investigating the evidence present in contextual settings in order to answer the research questions (Gillham, 2000). Yin (2018) defines case study as “an empirical method that investigates a contemporary phenomenon in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident”. Further, Woodside (2010) asserts that case study strategy focuses on “describing, understanding, predicting, and/or controlling the individual case”. Since this research aims at gathering empirical data to explore and understand the perspectives of different value chain actors, the case study is chosen as an optimal research strategy for this research.

The case study in this research incorporates multiple case study strategy for several reasons. First, studying multiple cases is necessary because the research aims at understanding the perspectives of different value chain actors who could have partially or entirely different motivations and challenges to component reuse practices. Second, through multiple case study, it is possible for the researcher to analyze how different digital technologies have enabled or can enable different component reuse practices for each value chain actor. Third, the multiple case study strategy can reduce the researcher bias and improve the external validity of the research (Voss et al., 2002). Finally, since a single source of evidence might not be a sufficiently valid, the cross-examination of multiple cases could substantiate the potential findings of the research (Yin, 2018).

3.2 Case Selection

This case study in this research employs purposive sampling principle for case selection, which implies a purposeful selection of cases rather than a random selection (Eisenhardt, 1989). The purposive sampling is driven by practical and pragmatic considerations of research objectives (Emmel, 2013) where the goal is to select the most insightful or informative cases to address the research questions (Patton, 2002). Consequently, a non-probability sample (Saunders et al., 2019) was created wherein the selected cases have different roles in the value chain and corresponding approaches to digital technology applications for component reuse. Through this rational approach to case selection, researcher aims to understand what the value chain actors' motivations and challenges for component reuse are, and how different digital technologies can successfully enable component reuse practices.

For creating the preliminary pool of potential cases, different secondary sources were utilized, such as researcher's network, expert consultation, and websites. Next, some specific criteria were used to select the cases from the preliminary pool. First, the cases should be involved in or striving for component reuse and should have adopted or working on adopting at least one of the selected digital technologies for advancing the reuse practices. Second, the cases assume the role in value chain as a designer, construction contractor, deconstructor, manufacturer, or a remanufacturer. Though the value chain involves several other actors such as maintenance company, logistics companies and end-customers, this research has not studied them for the sake of research feasibility and focus. Finally, the cases should be able to appoint an expert or an employee in authority position who could partake in interviews, on behalf of the case organization, to provide insightful answers. To decide on the befitting cases, based on the criteria, the expert network and connections of the stakeholders in ReCreate project were utilized.

Several of potential case companies were identified and the pool of potential cases were created. Next, the most suitable experts within the company were identified and they were requested for the interview. While many of the attempts to confirm the interviews with case companies failed, some were willing to provide the interview. Consequently, 10 cases were finalized, out of which 6 companies represent the construction sector and remaining 4 represent the manufacturing sector. Furthermore, an interview was conducted with a researcher from KTH Royal Institute of Technology, who has expertise in sustainable building technology. Though this interview is not a part of case analysis, insights from this study has been rather instrumental in the data analysis and inference process. The technical details of the interviews, including the positions of interviewees in the case organizations, are presented in Table 3 and 4.

Table 3. Technical details of the interviews in construction value chain.

Case Organization	**Role in the value chain**	**Position of interviewees in case organization**	**Date of interview (2022)**	**Duration of interview**
Company A	Designer (Architecture)	• Principal owner	4th April	101 min
Company B	Designer (Architecture, deconstruction design, consultancy)	• Business development manager • BIM development manager • Project manager	19th May	78 min
Company C	Precast manufacturer	• Technology manager • Business development manager	13th April	85 min
Company D	Precast manufacturer	• Technology director	5th April	72 min
Company E	Deconstruction contractor	• Project manager	26th April	83 min
Company F	Construction contractor	• Project manager • Business development manager	3rd May	82 min
KTH	Knowledge co-creator and disseminator	• Associate professor, Sustainable building	3rd May	64 min

As shown in the tables above, the case companies' names are kept anonymous to ensure their privacy. The companies in construction sector are named Company A, B, C, D, E and F. Respectively, among the six of these case companies representing the construction industry, two are designers, two are precast concrete manufacturers, one is demolition contractor, and last one is constructor.

Table 4. Technical details of the interviews in manufacturing value chain.

Case Organization	**Role in the value chain**	**Position of interviewees in case organization**	**Date of interview (2022)**	**Duration of interview**
Company W	Designer, Manufacturer, Re-manufacturer	• Head of Industrial IoT • Head of sustainable manufacturing	25th April	61 min
Company X	Designer, Manufacturer, Re-manufacturer	• Team leader for remanufacturing	27th April	60 min
Company Y	Designer, Manufacturer, Maintenance, Remanufacturer	• Technology director	18th August	63 min
Company Z	Designer, Manufacturer, Re-manufacturer	• Sustainability manager	19th August	64 min

As shown in Table 4, the case companies in manufacturing industry are named Company W, X, Y, and Z. In the manufacturing industry, though the original goal was to find companies with distinct roles in value chain, as in construction industry, it was not possible mainly because the manufacturers often assumed multiple roles themselves, such as designer, manufacturer, maintenance operator, and remanufacturer. Nevertheless, the interviewees were able to provide their views from several standpoints.

3.3 Data Gathering

Case study research can employ either quantitative, qualitative, or mixed approach for data collection. For this research, the qualitative method is most suited because the study is both exploratory and explanatory (Gummesson, 1993). The qualitative data can be gathered through several methods, such as interviews, questionnaires, observations, and documents analysis (Gillham, 2000). According to the complexity of the cases, more than one method can be used. However, for this research, Qualitative interviews are chosen as the optimal method to gather the primary data.

Additionally, the primary data gathered through interviews are further analyzed in the light of secondary data, such as the case organizations' websites, internal and external reports, news articles, technical documents, and other publications (Gummesson, 2017). The use of data from multiple sources, on one hand, improves the reliability of research (Voss et al., 2002), while on the other hand, helps the researcher interpret the underlying phenomena rather objectively. Besides, the data from multiple sources can be compared for their convergence, which supports data triangulation in this study (Eisenhardt, 1989).

The qualitative interviews carried out, between April and August, were elite interviews, wherein the interviewees were experts and held authority positions in the case organizations, and could provide insightful answers (Gillham, 2000). Additionally, all of the interviews were semi-structured. The semi-structured interview was a deliberate choice because the researcher could adopt more tailored strategy to conduct each interview. The researcher could clarify the issues remarked by the interviewees, for instance through inquisitive and follow-up questions (Bhattavherjee, 2012). It was important to acknowledge the fact that when the researcher gains firsthand understanding of the context, new questions may arise and evolve (Gillham, 2000).

The researcher understands that the integrity of data should not be compromised in any manner. Hence, the interviews were conducted professionally and objectively; no interviewees were imposed or influenced in saying what they did. Before the interviews, structure or the themes of interview were sent to the interviewees, so that they can get familiarized with the potential topics of discussion and prepare for it if necessary (Saunders et al., 2019). Due to the differing roles of the case organizations in value chains and different backgrounds of interviewees, questions could not be replicated. Rather, each interview consisted of questions that were most relevant to the case in study. The themes for interview, sent to the interviewees, are attached in Appendix A.

In total, 10 interviews were carried out, each lasting between 60 to 90 minutes. With the permission of the interviewees, the interviews were recorded in audio visual format.

Moreover, the researcher made notes during the interviews (Patton, 2002), that served three purposes. First, it helped the researcher formulate clarifying questions and probes that arise during the interview. Second, it accounted important non-verbal cues of the interviewees, that would facilitate analysis of the interviews, later on. Finally, it rendered interviewees a sense of researcher's engagement. Post-interviews, the recordings were transcribed by the researcher for further analysis (Evers & Boer, 2012), except two interviews were sent for external transcription and reviewed by the researcher.

3.4 Data Analysis

The current study employs both deductive and inductive approaches to qualitative analysis (Yin, 2018). While the deductive analysis aims at testing a theory or hypothesis that is conceptualized based on prior knowledge, the inductive analysis aims at theory building when there is not enough previous knowledge on the subject or if the knowledge is dispersed and inconclusive (Elo & Kungäs, 2008; Bhattacherjee, 2012). For the first part of the research, at the outset of case study, the deductive analysis was primary strategy to synthesize the findings from literature review. Then, in the second part of the research, inductive analysis was principal for the abstraction of case study data.

However, it is important to acknowledge that the inductive and deductive strategies are not mutually exclusive analytical approaches, rather it is their interplay that is critical for effectively addressing the research objective (Corbin & Strauss, 2008). For instance, Patton (2002) argues that the qualitative analyses are often inductive in the early stages, wherein inductive analysis involves coding the data and establishing patterns, themes, and categories; the later stages of qualitative analyses are often deductive which involves interpreting the categorized data to form theories or propositions. Nevertheless, the process of induction and deduction are not necessarily linear; rather, they are often complementary to each other.

The primary data, transcripts and notes, gathered through interviews reflect the relativist perspectives and complex intricacies of reality. Therefore, the goal of data analysis is to clarify and rationalize the complexities in such a way that the research questions can be answered (Patton, 2002). The researcher began the data analysis with a within-case analysis, offering an overview of how digital technologies facilitated component reuse in each case and, as a result, mapping the linkages between the use of digital technologies and value creation in each case organization. Subsequently, the researcher moved on to a cross-case analysis, in which researcher evaluated the cases to identify and interpret correlations across them. The general research process of this study is presented in Figure below.

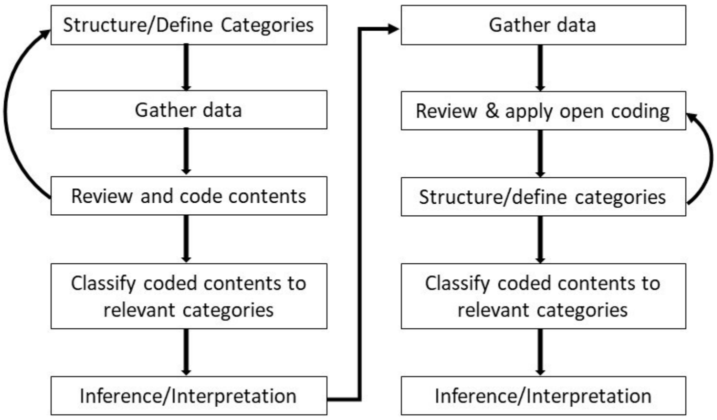

Figure 15. General process of literature review (left) & case study analysis (right).

As the first step in within-case analysis, preliminary categories were defined based on the categories or themes from the literature synthesis. Next, open coding strategy was used for coding and categorizing the significant information from the interview data. The transcripts were reviewed, and the key contents were linked to different codes following the coding strategy. Whenever there was crucial information that did not fall under the predefined categories, a new category was defined and a new code was created.

As the fourth step in the analysis, the categories were examined based on two criteria, namely the internal homogeneity and external heterogeneity (Patton, 2002). Whereas the internal homogeneity implies similarities and correlation among the contents in a category, the external heterogeneity implies the distinctiveness between the contents in any two categories. To fulfill both the criteria, when necessary, the categories were redefined, or new categories were added. In the following step, the transcripts were reviewed again, rather rigorously, to ascertain whether any significant information is left out. Any substantial new information was coded and classified to the most relevant category; when necessary, new categories were created to incorporate the new content.

As the final step of within-case analysis, the contents across all categories were reviewed and amalgamated to derive concrete findings. Additionally, the researcher used secondary data, notes, and insights from the interview with KTH to support the inferential process. After the within-case analysis, the inferences from different case studies were juxtaposed to abstract logical conclusions or propositions. Most importantly, the findings drawn from the case studies were synthesized to address the research questions.

4. RESULTS AND ANALYSIS

This section compiles and analyses the results from the multiple case studies, in an attempt to answer the research questions. This section is divided into five subchapters, where the goal of first four subchapters is to answer the research questions 1, 2 and 3; and the final subchapter attempts to answer the research question 4. Whereas Chapters 4.1 and 4.2 are focuses on the findings from the construction industry, Chapters 4.3 and 4.4 focuses on the findings from manufacturing industry. Chapter 4.5, then, juxtaposes the findings from both industries to answer research question 4.

First, Chapter 4.1 presents the views of the construction value chain actors regarding their motivations and challenges for structural component reuse. Second, Chapter 4.2 presents the perspectives of the construction value chain actors on how BIM, IoT gadgets, and Robots could be utilized for advancing the structural component reuse practices. To providing a holistic understanding to the readers, Chapter 4.2 also presents the challenges of using the digital technologies, but in very brief. Third, Chapter 4.3 presents the perspectives of manufacturing value chain actors what their motivations and challenges are for component reuse or remanufacturing. Next, Chapter 4.4 presents their perspectives on the applicability of digital twin, IoT-gadgets, and robots for facilitating remanufacturing practices. Finally, Chapter 4.5, renders the similarities and differences in use of selected digital technologies, for component reuse practices, in construction and manufacturing.

4.1 Motivations and Challenges for Structural Component Reuse in Construction Industry

Even though structural component reuse could have been a reality in the construction industry by now, evidence shows that it is not. As the interviewee from Company A pointed out, the global understanding of economics in the past was rather shortsighted which put particular emphasis on what happens at the present but completely ignored what happens in the future. The interviewee recalls that climate needs were not taken seriously enough in the past by companies and people, perhaps because the effects of climate change was not as critical as it is today. An interviewee from Company C made a similar remark:

"No one really, seriously, talked about sustainability on the first 20 years in my career. ***There was hardly any discussion about CO_2 emissions and reducing that****. … Now we have climate as one of the pillars in our strategy, that's very important for us as a company." (Company C)*

However, all the interviewees from the case companies share the same view that recently the companies and people have become much more aware and concerned about the need to protect the planet through preservation of resources that are in the nature or in circulation already. They concur that such environmental awareness has been the intrinsic motivation for the companies to rethink their economic models and try to incorporate component reuse practices in their operations. Nevertheless, interviewees pointed out several other motivations or reasons for the case companies to make this transition. Following table presents the lists of motivations that are recognized by the value chain actors.

Table 5. Motivations for structural component reuse for value chain actors.

Motivation for Structural Component Reuse	**Designers**	**Precast Manufacturers**	**Deconstructor**	**Constructor**
Sustainability as company strategy	A, B	C, D	E	F
Experience advantage	A, B		E	F
Legislative changes	A, B	C, D		
Influence or demand from customers		C	E	
Potential resource scarcity or material price escalation	B	D		
Opportunity to capitalize on residual value of elements	B	D		
Customers might get tax benefits				F
Willingness of companies (customers) to invest in reused elements				F

As shown in the table above, the main reason why companies have started to be involved in component reuse practices is their sustainability strategy. All of the case companies mentioned that environmental sustainability has been duly considered in their strategic plans. For instance, Company D has set a specific target for carbon emission reduction. Since component reuse is one of the most effective ways of reducing carbon footprint, it has been recognized by the companies as a path that is worth exploring.

Second, all of the case companies, except precast concrete manufacturers, mentioned that by adopting component reuse practices now, they intend to gain an experience advantage. The companies seemed aware that component reuse practices are going to be important aspects of their operations in the future. Hence, by already getting involved in such practices, they can learn a great deal how things should be done. The interviewee from Company A for instance implies that being a forerunner in this direction allows a company to gather the expertise on best practices and gain a better understanding of difficulties, risks, and opportunities that follow. Along the same line, an interviewee from Company B said:

"… with the development of cities and societies, it is impossible to try to stop people from making new buildings. However, which way they are built or with which materials, that can be affected. This is why ***we want to develop the ways to do this (component reuse) and be ahead of it and provide the consultancy for it****." (Company B)*

Third, the legislative changes were considered an important driver by the designers and precast manufacturers. The national as well as international legislation are increasingly moving towards the direction that a percentage of old building needs to be preserved or kept intact instead of destructive demolition. The Eurocodes for instance has paved the way in that direction, at least in EU. Additionally, the local and national carbon neutrality targets for example have driven or forced the companies to adopt similar goals in terms, thus promoting the component reuse practices.

Fourth, the influence or demand from customers were emphasized as an important motivation by the precast element manufacturer and deconstructor. As the customers are getting more aware about need and implications of circular economy, the precast manufacturers deem it necessary that they consider the reusability of their concrete element products. As one of the interviewees from Company C mentioned, the clients are increasingly asking for environmental product declarations (EPD) and carbon footprint calculations. This means, by adopting component reuse practices, precast element manufacturers could gain a competitive edge over their competitors. On the deconstruction side, the demolition company's customers or the building owners are also increasingly demanding explicitly that the demolition company recover certain percentage of the building components and materials.

Fifth, the potential raw material scarcity and price escalation was considered the motivation for reuse by the designer and precast element manufacturer. With the increasing political polarity of the countries and depleting stocks of virgin natural resources, the raw material markets could become volatile at any given time in future. Consequently, as an interviewee from Company B speculates, raw material prices could skyrocket or become completely scarce (due to political or natural reasons). By opting to component reuse practices, construction companies could prepare for such situations that would otherwise disrupt their profitability or the operations altogether. The interviewee company B mentioned:

"I just saw a project's price becoming more than double than estimated, because of market situation. So, ***prices are double suddenly because it's just so difficult to get any materials now*** *in. And* ***there's a lot of insecurity in workload also, but the materials and products and projects ongoing in particular****. So, this is unbearable situation for us nationally but internationally too. So, that drives, that motivates me to go forward…". (Company B)*

Sixth, a designer company and a precast manufacturer emphasized the opportunity to capitalize on residual value as motivation for component reuse. Several studies have established the fact that structural elements have very long service life. When buildings are demolished, and many of them are demolished even before their expected life, the structural elements can be recovered instead of destroying to rubble. The recovered elements can be capitalized in two ways. First, they could be sold and thus create monetary returns. Second, using the old element in new building could offset the carbon footprint of both the old building and the new. As the interviewee from Company D said:

"… we have a lot of existing buildings with very long service life products. So, that benefit is something that should be taken into account." (Company D)

Finally, the tax benefits for customers and willingness of companies to invest in buildings with reused components are recognized as motivations for structural component reuse by the constructor. An interviewee from Company F implied that customers, in the future, could get abated from carbon emission tax if they use old elements instead of new ones. Such customers could also benefit from easier funding and subsidies. Another interviewee pointed out that companies, in comparison to private persons, are becoming more aware and willing to buy or build a building that uses old element. This directly and indirectly motivates the construction companies to employ reused elements in new buildings.

While there seem to be several motivations for the value chain actors to adopt structural component reuse practices, it is not free from challenges. In fact, there seem to be more challenges at the moment, perhaps because it is a new direction that is being explored very recently. The challenges mentioned by the value chain actors are listed in Table 6. Interestingly, most of the challenges pointed out by the interviewees are not completely disparate from each other but rather reinforcing.

Table 6. Challenges to structural component reuse.

Challenges of Component Reuse	**Designers**	**Precast Manufacturers**	**Deconstructors**	**Constructors**
Perceived uncertainties regarding quality and risks of using old elements	B	C		F
Need a large database or platform to show the availability reused components	A	C	E	
Lack of historical information such as assembly sequence, material composition, maintenance, and modifications	A, B	C		
Lack of business models and standard procedures for sales and procurement of reused components	A	D		
Difficulty in providing warranty		C		F
Logistics costs might reduce potential cost savings for customers		C	E	
Reuse needs more efforts	A			F

Currently deconstruction is more expensive than demolition	B		E	
New precast elements are very price competitive	B			F
Different ways of manufacturing concrete elements across countries	A, B			
Different legislations across countries	A, B			
Bold and effective legislation or local policies are yet to develop	B			
Common standards such as Eurocodes still not entirely adopted in private sector		C		
Carbonation of concrete		C		
Customer's resistance to change				F

First, the perceived uncertainties regarding the quality and risks can be a challenge for structural component reuse. Since there aren't many examples of structural component reuse in the past, best practices or standard guidelines do not exist yet. As an interviewee from Company F suggested, currently the constructor itself cannot be entirely sure of the risks that may prevail in the future. Which in turn creates contract complications, for example, what sorts of risks related clauses to put in contract when selling a building with reused structural components. Another interviewee from Company B suggested that customers tend to be ambiguous whether the old elements have same quality as new, for instance, in terms of indoor air quality, mold resistance, and load bearing capacity. In the same line, another interviewee from Company C provided a future perspective. If in the future, for the sake of easier disassembly and reuse, structural components joined mechanically instead of casting, could that compromise the acoustic performance and stability of the building?

The second challenge to structural component reuse is associated to ensuring the accessibility to and visibility of old components. To ensure that all potential buyers have the knowledge and real-time accessibility to old structural components, a large-scale online database or library is required where existing inventory of old elements can be showcased for sales. Since such a large-scale database does not yet exist, the ownership, functionalities, and management dynamics of such a platform are still to be explored. As the interviewee from Company E implied, without the access to information about existing structural elements, such as dimensional and physical attributes, it becomes rather difficult for building designers to incorporate the old elements in their designs. The interviewee remarked:

"…everything starts from the designing. And there could be also some kind of database where it should be listed which elements can be reused… ***when somebody is planning a new building; they could check there in the database some old element that they could use in the new building. Then they could take dimensions (of the old elements) into account on designing phase (of new buildings).*** *" (Company E)*

The third challenge is related to currently existing buildings that were designed in the past. Many of the old building today lack the historical information regarding their assembly sequence, material composition, maintenance and modifications, which are rather critical information from both the design and quality point of view. Fundamentally, the old buildings were not designed with future circularity in mind, and therefore, such information were hardly recorded. For instance, the interviewee from Company A pointed out that the old buildings could have a certain design on paper, but it could have been built slightly different during actual construction, not to mention the changes in the future. He implied that such changes were not properly documented in the past.

Fourth, the lack of business models and standard procedures for sales and procurement of old elements is another challenge. The current business models in the construction industry are predominantly based on the sales and procurement of new elements and not the old. Consequently, there is natural inertia among the companies to continue their existing model rather than changing it. Moreover, due to lack of previous trades of old elements, at least in the apparent scale, there does not exist a set of standard practices how such trades are carried out among stakeholders. This challenge was reflected by an interviewee from Company D:

"… if there is a stakeholder that has some kind of library (of existing inventory), ***what kind of elements will it be creating? What will be the design procedure for those elements?*** *Will it, for example, cut the elements to standard modules of similar dimensions, or will it prepare them according to the need of new building? Because the elements from different sources will be different" (Company D)*

Fifth, difficulty to provide warranty was considered another challenge. As one of the interviewees from Company F suggested, it is rather difficult to get a CE mark on the old structural components. Particularly, when there is lack of historical information about an element, understanding the quality of the element is challenging. Which in turn makes it difficult to determine a justified warranty period and warranty terms. As the interviewee from Company C pondered:

"…another issue, I think, is around the warranties. …It's little tricky. ***How do you consider the elements that you have already used?*** *It's one of the issues you might face." (Company C)*

Sixth, potential high logistics costs can become a challenge for structural component reuse, because that could significantly deteriorate the economic savings for customers. Reuse of structural component involves several logistical processes, such as lifting, handling, inventory management and transportation. Costs of those functions could increase the price of the elements, particularly when the transportation distance is far. The logistics processes are challenge in themselves because the old buildings elements were not designed with ease of handling in mind. Not to mention, some of the structural component might get damaged during the aforementioned processes, which means the logistics costs get distributed even higher among the remaining elements.

Seventh, simply the need to put in more efforts can be a challenge for reuse. According to the interviewees from Company A and F, getting an old element usually need a lot more work than buying or making a new one. The eighth challenge is that currently deconstruction is more expensive than demolition. Since deconstruction requires more technologies, planning, and resources than demolition, it is less economic. This leads to the ninth challenge that new elements are already price competitive. Due to a long history of factory production of structural elements, they are produced rather simply and efficiently. As the interviewees from Company B and F said, new hollow-core slabs are already very cheap and therefore it is difficult for the recovered hollow-core to compete in price. The interviewee from Company B remarked:

"We cannot use time and resources for anything that is not a necessity. Because ***we need to do this as low cost as possible or kind of provide process that is as cheap as possible. Because we are competing with products that are very lean, they have had, kind of, 50 years of time to do this as cheap as possible****. So, for example, a hollow-core slab is so cheap that it's very difficult to compete with price." (Company B)*

Next, other challenges are associated to differences across countries in terms of their legislative policies and product standards. Moreover, while the interviewee from Company B pointed out the hesitation or failure of policymakers, at regional national or international level, to set bold and justified regulations as a challenge, an interviewee form Company C also pointed out another challenge, that is the slow adoption of common standards, such as Eurocodes or En 206-1:2000, across the private sector.

Finally, carbonation of concrete and customers' resistance to change were also identified as challenges to structural component reuse by Company C and Company F, respectively. While the carbonation of concrete is a technical challenge that can be resolved or eliminated with certain technological measures, the customer's resistance to adopt reused elements is subjective. As an interviewee from company F implied, even though people are aware of the environmental benefits of reusing existing structural components, they might nonetheless prefer the buildings with new elements. However, the interviewee also acknowledged that it is the seller's responsibility to communicate the value of structural component reuse, in a way that customers become more susceptible:

*"I think **it's a challenge of communication and how we share the information, and how we tell the story and sell it to the customers**. I think that's the key point in a way. It's a bit like mindset thing." (Company F)*

4.2 Perspectives of Value Chain Actors on Use of DTs for Structural Component Reuse

4.2.1 BIM

This study made it evident that BIM has been one of the digital technologies that the construction industry has substantially accepted. In one way or another, all of the value chain actors have been working on BIM. It has grown to be a crucial tool for architects and designers when designing new buildings and structures. Similarly, the precast manufacturers use it to design precast concrete elements while also integrating it to their ERP system to guide production and visualize the components to potential customers. Additionally, BIM is used by the deconstructors and constructors to plan and guide their workers on how to carry out demolition and construction, respectively. Nevertheless, this study supports prior studies that BIM has not yet been a significant technology in terms of structural component reuse. The value chain actors in this study have, nonetheless, identified a few ways how BIM Models could support structural component reuse practices; these are listed in the table below.

Table 7. Potential uses of BIM for structural component reuse.

Uses of BIM	**Designers**	**Precast manufacturers**	**Deconstructor**	**Constructor**
Can act as presentation material	A	D	E	F
Detailed information can be assigned to elements	A, B	D		F
Historical information can be recorded		C		F
Supports deconstruction planning	B		E	F
Guides the actual works of deconstructors, constructors, and designers	A, B	D		F
Can be connected to ERP system		D		
Can be connected to IoT gadgets for tracking and monitoring the elements		C, D		

First, a BIM model can act as a presentation material because it visualizes the drawings and the structural elements rather conveniently. This functionality of BIM was considered valuable by all value chain actors because the visualization makes the communication among stakeholders much easier. As an interviewee from Company F suggested, in comparison to 2D drawings, a BIM model makes it easier to understand the space and dimensions of the buildings or the elements. Moreover, the 3D visualization makes it easier for the deconstructor to plan how the component recovery process should be carried out effectively.

Second, an incredibly detailed level of information can be assigned to BIM models. For instance, the designers and precast manufacturers suggested that each structural element in the model can be attached with pdf documents, quality notes, QR codes, and external links that that relevant for the element. The model could also store other static information (that does not naturally change over time) such as physical attributes and structural composition of elements as well as building assembly sequence. Those sorts of information are valuable for structural component reuse because they can be used to plan deconstruction procedures, design future buildings, and to assess quality. The interviewees from company A and B made following remarks:

*“**It (BIM) allows you to go into incredible detail if you want to**. You can spend hours and hours of time detailing a specific beam, for instance. But then again, ‘is that useful’ is a good question. So, what is the question that you're trying to address when you have it all (the details)?” (Company A)*

*“In my opinion the **most important part of BIM model is the information**. If you don't have the information, you have just graphics.” (Company B)*

Third, BIM model can record and update historical information (that changes or gets changed over time) associated to the structural elements. Information such as use conditions, modifications, and maintenance history can also be updated into the BIM model throughout the element’s lifecycle. Such historical information are critical for structural component reuse because they allow realistic assessment of quality and durability of the components.

Fourth, BIM models can support deconstruction planning in varieties of ways. For instance, when a BIM model records static and historical information of a building and its components, based on that information, a deconstruction company could formulate the most suitable strategy to deconstruct the building. As the interviewees from company E and F suggested, the information from BIM model can become valuable when deciding how the elements can be safely and effectively detached, in what order the components should be removed, and how the components should be handled during recovery operations. Moreover, the interviewees from Company B and E pointed out that BIM models can be effective tool to calculate time and resource needs of recovering and reusing a structural component. The interviewee from Company E said:

*“Now, the most use of the model is on the designing phase (of deconstruction work) **when we are designing all the plans and how the actual (deconstruction) work is going to be**. But it can be used also **when the company is assessing the job like how much resources are required and how much it will cost**.” (Company E)*

Fifth, a BIM model can guide the actual works of deconstructors, constructors, and designers, particularly because of the information storage and visualization functionalities of BIM. For instance, a deconstructor can guide its workers by showing on BIM model, which order the components should be detached and how the elements should be handled. Basically, through BIM, the deconstruction plan can be easily and effectively communicated to the workers. Additionally, if designers have access to the BIM model of an existing building or components, they can take into account the old elements when designing the new building. On the other hand, if a deconstructor or a constructor has the BIM model of the new building, they can cut the old components into necessary dimensions that fit to the building accurately. Moreover, the constructor could guide its workers how the components should be handled and used. For example, an interviewee from Company F said:

"I believe we can use the BIM model when we start this work (construction of new building). ***We can show our workers where we start, how that continues, which pieces we take first, what kind of safety things we need, and how we use those safety things****. We can even, for example, plan every week differently..." (Company F)*

Next, BIM model can be connected to IoT gadgets that are attached to the physical components. The IoT gadgets such as sensors and RFIDs could track and monitor the structural components throughout their lifecycle and relay the data to BIM model in real time. As the interviewees from Company C and D suggested, IoT gadgets, such as sensors, could measure the component's deflection, temperature, moisture etc. and transfer those measurement data to BIM. In turn, the data can be used to 1) plan predictive maintenance so that the components do not get damaged during their lifecycle and 2) assess the components' quality or reusability once they reach end of life. Finally, BIM model can be connected to ERP systems, this has several implications in the context of component reuse. For instance, an online library or database of existing components could transfer the data from BIM models to its ERP system, for effective inventory management, customer order management, and refurbishment planning.

In addition to the aforementioned potential uses of BIM, the value chain actors mentioned a few other benefits of using BIM that can be valuable in the context of structural component reuse. For instance, the interviewee from Company D suggested that BIM is indirectly promoting harmonization or the standardization of dimensioning, visualization and information attachment procedures, because almost every designer today works on BIM. Also, the interviewee from Company A implied that BIM is becoming more easier to use and designing with BIM is faster. Moreover, an interesting remark was made by an interviewee from Company B, who said that BIM is a convenient tool to calculate the mass of structural components, which was rather tedious process in the excel.

Improvement Areas in BIM

Since BIM was not originally developed to facilitate structural component reuse, it has some limitations that could be improved upon in the future. In this study, the value chain actors suggested a few improvement areas for the existing BIM softwares. For instance, the interviewees from Company A, D and F suggested that BIM software could be developed into a collaborative platform where different value chain actors can work and share ideas in real time. Traditionally, architects, structural engineers and precast manufacturers create separate BIM models, and there is not a standard mechanism how the data from different stakeholders are combined. Consequently, the information associated to the building and its components are dispersed, and there is a high probability that not all relevant information are saved or passed on to the constructor or building owner. This is linked to the improvement area suggested by the constructor. According to an interviewee from Company F, the original BIM model should be available for all value chain actors including the building owner. This can help structural component reuse in two main ways. First, the building owner could record and update historical information to the BIM software, thereby improving the traceability of the structural components. Second, when building reaches end of life, the building owner could transfer the BIM model to the deconstructor who will have access to varieties of information that will help in deconstruction planning.

However, sharing an information rich model openly with different stakeholders raises the question of data security. In other words, BIM should have a mechanism to ensure that a stakeholder along the value chain is able to access only those data that are necessary for it. The software could also define what sorts of data or model attributes a specific stakeholder has the right or permission to change. Additionally, the interviewees from Company A and D suggested that BIM could have a traceability feature that could track the changes made to the model and also record who made those changes. For this functionality, BIM software could develop connectivity and compatibility with other technologies such as Blockchain. The flexibility to work with Blockchain technology and other technologies such as AR, VR, and 3D printing is something BIM softwares could be developed for in the future. However, new research are required to assess the need and feasibility of this development and how significantly can such developments support structural component reuse.

Another important improvement area suggested by the interviewees from Company A, B and D is associated to standardization of information formats in BIM. Since a BIM model can be filled with a lot of information, it is important to distinguish what are critical information and what could be the standard parameters. In other words, across BIM softwares, there should be a common standard- what sorts of information are stored by the stakeholders and in what format. This would make information transfer process across value chain more streamlined and efficient.

Additionally, the interviewee from Company A suggested that the BIM softwares still have room to improve their features that can incorporate the building designs from past and also the building designs from geographical or cultural background. Finally, it was proposed that standalone versions of BIM software (that which does require internet connection to function) could be developed, instead of providing solely the internet-based versions. He argued two benefits of it. On one hand, the necessary work in BIM could be carried out even if internet connections are disrupted. On the other hand, sensitive or confidential information in BIM model could be protected from cyberattacks.

Challenges of BIM

It was evident that BIM could be a useful tool to support various structural component reuse practices, such as component traceability, information transfer, deconstruction planning, inventory management, quality assessment, and design with reused components (DwRC). However, in addition to the previously mentioned improvement areas, there are several other challenges of using BIM for the component reuse purposes. Four major challenges were identified by the value chain actors, that are presented in the table below.

Table 8. Challenges of BIM applications in structural component reuse

BIM challenge	**Designers**	**Precast manufacturers**	**Deconstructor**	**Constructor**
Lack of sufficient information to create a proper BIM model of existing buildings or components.	A, B	C	E	F
Resistance to adopt BIM	A		E	F
Use of different BIM software	B	D		

Tedious process to translate different information to BIM model	A	D		

The first challenge was the lack of sufficient information to create a proper BIM model of an existing building or a structural component. There are several reasons for this. For instance, the interviewees from Company A, B and C pointed out that many of the old building designs are lost due to poor archiving and document management systems in the past. While many of the old building designs can still be found, they are often the 2D drawings which provide very little or no information regarding the materials used, component interconnections/joints, internal structures (e.g., rebar grids), and use conditions. Not to mention, the old structural components can have different dimensions than what is specified in the original drawings. Moreover, the historical information associated to the buildings or components, such as maintenance and modifications, are rarely recorded. This means that extra time and resources need to be invested for 3D measurements and quality assessments.

The second challenge is the resistance to adopt BIM. As an interviewee from Company F suggested, stakeholders in the construction value chain are yet to realize the full potential of BIM. However, the main reason for the resistance is lack of technical skills or motivation among workers to use the BIM models. Particularly the older generation, but also other workers, are accustomed to work with traditional 2D drawings or AutoCAD files, who are rather hesitant to learn and switch to the new technology. Additionally, it was also inferred by the interviewees from Company A and F that small companies might lack financial capabilities to work with the BIM softwares.

The third challenge is the use of different BIM softwares by different companies or individuals. Different BIM softwares have different functionalities, information formats, and different ways of identifying and updating information. In other words, there are different ways to do same thing in different softwares. Also, it was pointed out by the interviewee from Company D that there are issues in transferring a BIM model of an element to another BIM model, because the ID of that element is fixed to the model where it is originally created. These sorts of issues make it challenging to transfer information across different BIM softwares and makes it difficult to merge the different BIM models.

Finally, the process of translating different information to BIM is a tedious process, particularly when necessary information need to be garnered from different sources or the available information formats are not readily transferrable to BIM. This means that a certain amount of budget need to be invested into the information translation process. This process also necessitates time, and that can be a challenge in construction projects with tight schedule.

4.2.2 IoTs

IOT gadgets have been known for their ability to track and monitor products at different stages of value chain. For instance, sensors and RFID tags are considered to be useful for inventory management and real-time product monitoring for preventive maintenance. Additionally, they have also been recognized for the ability to optimize logistics operations through increased visibility. However, the use cases of IoT gadgets in the reuse context are quite rare, mainly because the structural component reuse is a new dimension of circular economy that is starting to be explored only recently. In this study, as well, the value chain actors had not been using the IoT gadgets to advance the structural component reuse practices. Nevertheless, some of the value chain actors have recognized a few potential applications of IoT gadgets for facilitating the component reuse practices, which are listed in the table below.

Table 9. Potential uses of IoT gadgets for structural component reuse.

Uses of IoTs	**Designers**	**Precast Manufacturers**	**Deconstructors**	**Constructors**
Components can be tagged with corresponding component information,		D	E	
Can be attached to components to monitor quality and performance		C, D		
Can be connected to BIM for recording and updating component lifecycle information		C		

First, RFID tags can be attached to the structural components and the component related information, i.e., static information, can be stored into the tags. This approach is similar to the idea of distributed BIM library proposed by some of the literatures. Tagging of the element can happen at two stages of component lifecycle. According to the interviewee from Company D, the RFID tags can be casted into new structural components when they are manufactured and, thereafter, the tag follows the component throughout its lifecycle. This allows the traceability of the components throughout the value chain; desirably, also when the component is disassembled and being prepared for second life use. Next, according to the interviewee from Company E, when structural elements from old buildings are disassembled, RFID tags could be attached to the components. The tags could contain component related information such as design attributes and previous use conditions. Further, the RFID tags can be connected to an online database for inventory management.

Second, the precast manufacturers infer that IoT gadgets such as sensors or RFID sensors could be attached to new structural components; consequently, the gadgets can monitor the quality and performance of the components. For example, an interviewee from Company C pointed out that the gadgets could measure the deflection and stability of the components. Similarly, the interviewee from company D suggested that the gadgets could be used to monitor moisture and temperature of the components. Below is the remark from an interviewee from Company C:

"When we are finished with the BIM model and we have erected the building, then we are into some kind of maintenance things. So, if we can use the BIM model during that thing, for example, for checking the deflection, we can ***actually add information into the model during the lifespan****. …****talking about sensors, you can connect the sensors to 3D model so you can actually get that information online****." (Company C)*

Finally, the IoT gadgets, attached to the components, can be connected to BIM for recording and updating corresponding lifecycle information. The static information stored in the gadgets and the historical information gathered by the gadgets can be relayed to a BIM model in real time, where the information are stored and updated. In turn, the visibility of the components' lifecycle information can support their reuse in two ways. One, it allows predictive maintenance, which in turn improves the durability of the components. In other words, the integrity of the structural components can be maintained such that, when they reach end of life, they are fit for second life use. Next, the information can be used for more accurate quality assessments of the components when they reach end of life. Moreover, if the BIM models of the structural components are linked to a database that can be accessed by designers, the designers can take into account the structural components when designing new buildings.

However, for the IoT gadgets, i.e., RFIDs and sensors, to be used in reuse context, the value chain actors suggested that a few things need to change. According to the interviewees from Company B, C and D, the gadgets are expensive currently and, therefore, attaching them to the structural components is costly. Particularly when considering the price of hollow-core slabs which is already a cheap product, attaching the expensive gadgets could deteriorate their price competitiveness. Therefore, the interviewees argued that the price of those gadgets need to go down further before they can be attached to structural components. An interviewee from Company D, for example, said:

"…there have been some project also to check whether we could follow the moisture and such. And it's possible, it's bit challenging in concrete because you need to cast those (IoT gadgets) into the concrete. So far, ***they have not been very reliable and they have been too expensive****, I think. So, it's easier to drill the hole and check the moisture out of the hole. And that's the way they are doing it nowadays." (Company D)*

Additionally, it was implied by the interviewees from Company B and D that there is an ambiguity whether the gadgets will have same functionality and relevance when the structural components reach end of life. In other words, if the gadgets are to be casted into the structural components, then their functional life should outlast the components they are casted into. Also, it was pointed out by the interviewee from Company D that gadgets and reading devices need to be standardized such that different gadgets can be conveniently read by a single stakeholder. This is important because different companies might use different types of gadgets, for example, RFID tags of different frequencies, that require different types of reading devices. Moreover, it is important to acknowledge that embedding the sensors and RFIDs into concrete is a challenging task and not yet a common practice. Therefore, further studies are required to assess how it can be done and whether they can affect the quality of structural elements.

4.2.3 Robotics

Whereas robotics automation is increasingly being recognized as one of technologies with potential to streamline manufacturing and production activities in the value chain, it is yet to be recognized for the potential to facilitate structural component reuse. While it is fairly reasonable that designers have no need to use robots for design works, neither of the other value chain actors in this study were using robotics automation to support the component reuse practices, including the deconstructor. However, the interviewees suggested that robots could be used in the future for automating different processes in structural component reuse context.

It was suggested by the interviewees from company A, D and F that robots could be used to automate repetitive processes during deconstruction, post-deconstruction component processing, and assembly. For instance, tasks such as cutting the elements, unfastening nuts and bolts, and cleaning could be partially automated, that is, humans could guide the robots to carry out those tasks more effectively. Additionally, the interviewees from Company D and F surmised that robots could be used to partially automate the assembly of reused elements in new buildings. For example, it was suggested that perhaps the drilling, bolting, and gluing/casting tasks could be carried out efficiently by the semiautomated robots. The interviewee from company D made following statement:

*"Maybe if we consider that we have some kind of solid elements which have been demolished from the building and we develop some kind of very standard way how to connect those solid elements into each other**, it could be that there is some kind of automated machine to create some kind of drilling and fixing or maybe gluing some bars or items into the element**. But maybe I'm thinking too far." (Company D)*

However, the interviewees pointed out two major challenges in using robotics automation for aforementioned tasks. First, the lack of standard structural components was considered a major barrier for the use of robotic automation. When the existing stock of structural components, from varieties of buildings, are considered, they can vary a lot in terms of shapes, sizes, material composition, and quality. Consequently, the robots need to be extremely flexible in terms of functionality and performance to handle such structural components. Following comment was made by an interviewee from Company F:

*"I think that robotics and machines like that probably we can use, but **no one developed those good enough, because we don't have enough standard production. If we had standard production, there would be possibility to use robotics**." (Company F)*

Second, lack of detailed information about the structural components can become a challenge for robot applications. On one hand, the currently available stock of old structural elements have very poor record of static and historical information. On the other hand, though the designs are available, the actual elements might vary physically from their original design. In both cases, it becomes difficult to assess and strategize how the robots can be used to handle the structural components. This notion was reflected by the interviewee from Company D, who remarked:

*"When we are deconstructing old buildings, the structures are quite different compared to new ones, so **it's quite hard to use automatization there, because there are usually no old plans how the joints and the structures are going, and there are almost always going to be some surprises**. Like when we are taking the structures, we can't see where they are going and if there are some iron or something else. There will always be some surprises that weren't in the plans or they are just done very differently than the plans." (Company D)*

4.3 Motivations and Challenges for Remanufacturing in Manufacturing Industry

In manufacturing industry, remanufacturing is not a radical new concept, but it is not yet a common business practice either. While some of the companies have relatively longer experience of component reuse practices, some are only recently considering this transition. Nevertheless, though rather slowly, the manufacturing industry is moving towards remanufacturing for a variety of reasons. In this study, the value chain actors provided different perspectives as to what their motivations are for remanufacturing. The views of the actors are presented in Table 10.

Table 10. Motivations of value chain actors for remanufacturing

Motivations for Remanufacturing	**Company W**	**Company X**	**Company Y**	**Company Z**
Increasing customer demand for sustainable products	✓	✓		✓
Sustainability as company strategy	✓	✓		✓
Potential disruption in existing supply chains	✓	✓		✓
Utilization of residual value	✓		✓	✓
Lower cost of remanufactured products	✓	✓	✓	
External influence	✓	✓		✓
Competitive advantage creation	✓	✓		

First, the value chain actors emphasized that the customer demand for sustainable products has been increasing in the recent times, and hence, to fulfill the customer demand, companies are more interested in adopting remanufacturing practices. As the interviewees from companies W, X and Z suggested, the businesses as well as individuals are becoming more and more ecologically conscious. As a result, pressure is placed on the upstream value chain actors to offer solutions that can drastically cut carbon footprints. The increasing demand for remanufactured products was rather evident in Company X which started its remanufacturing workshop almost fifteen years ago, and it has been growing ever since. The interviewee disclosed that the company is planning to expand its remanufacturing operations further in another continent. The increasing customer demand was also pointed out by the interviewee from Company Z, who stated:

"The big companies are aiming to reduce their own CO_2 footprint over their portfolios or over their projects. So, they are actually asking us to have circular materials… So, ***that's really a very strong customer demand****…" (Company Z)*

Second, the organizational commitment sustainability is one of the primary factors driving companies to participate in different component reuse practices. For instance, the interviewees from companies W, X, and Z stated that their companies have sustainability plans and carbon reduction goals, that can be achieved through circularity. For instance, a Company W interviewee mentioned that the company is setting carbon reduction targets and also declaring the scope 3 emissions based on GHG Protocol Corporate Standard. Similarly, the interviewee from Company X underlined that they aim to become a sustainable company by substantially reducing the carbon footprint, and therefore remanufacturing is crucial to them. Additionally, the interviewee from Company Z revealed that they have net-zero carbon roadmap, and therefore, remanufacturing is important way for decarbonization. For example, the interviewee highlighted that by remanufacturing, locally available resources can be utilized instead of cross border sourcing, thereby, reducing the carbon footprint of transportation.

Third, the value chain actors acknowledged that one of the reasons for remanufacturing is the potential disruptions in the existing supply chains. The interviewees from companies W, X, and Z concurred that resource scarcity can occur in the future because of limited natural resources. The interviewee from Company Z further suggested that the global supply chains are becoming rather volatile due to increasing geopolitical tensions. Therefore, by opting to remanufacturing practices, companies can utilize the resources that are tied to the existing products, which in turn reduces the consumption of virgin natural resources. Also, by utilizing the locally available resources that are tied to existing products, companies can, at least partially, limit the dependency on foreign supply markets. Along the same line, the interviewee from company X emphasized that they are able to supply remanufactured products to the customers, in case new parts are not available in the market:

"Sometimes, there are global shortages of the new parts and maybe we cannot even get new parts from our supplier. So, ***if we can keep this remanufacturing business up and running, we can provide remanufactured parts even though we are not able to provide new parts****." (Company X)*

Forth, through component reuse, remanufacturers can capitalize on the residual value of the components. Interviewees from companies W, Y, and Z emphasized this as one of the critical motivations for remanufacturing. The interviewees stressed that by reusing components from end-of-life products, both economic as well as environmental value can be captured which would otherwise be lost through landfilling or downcycling.

Fifth, remanufactured products typically cost less than their brand-new counterparts, which provides cost competitiveness to the suppliers and customers. According to the interviewees from companies W, X, and Y, these financial incentives are important, particularly for the products and components that are relatively expensive. Additionally, a Company W interviewee suggested that customers may save money on product technology updates if they chose to reuse some components while replacing others. The interviewee stated the following:

"The lifespan of that machine tool is not that short actually. You can change certain parts and renew it basically throughout lifetime. For example, after 10, 12 years of use, you can take CNC machine and renew its controller computer, then it becomes more capable… ***And changing those electronic components is let's say much more environmentally friendly and much cheaper compared to manufacturing of the whole structure****." (Company W)*

Next, the value chain actors recognize that external influence is one of the driving forces for remanufacturing transition. On one hand, the academic institutions and environmental groups are advocating the urgency of component reuse practices. On the other hand, legislative bodies are putting more policies in place to encourage remanufacturing practices at the local, national, and international. As the interviewees from companies W, X, and Z highlighted, environmental protection policies and regulations are putting more pressure on businesses to consider remanufacturing.

Finally, two of the value chain actors underline that the desire to gain a competitive advantage is motivation in part to shift towards remanufacturing. As the interviewees from company W and X suggested, carrying out remanufacturing practices can boost company's credibility in terms of sustainability, giving it a competitive edge to the company. For instance, many customers today base their purchasing decision on more than just the cost but also take into account the manufacturer's sustainability initiatives, environmental product declarations (EPD), and ESG investments. The interviewee from Company W also emphasized that choosing to engage in remanufacturing today means securing an experience advantage because remanufacturing would eventually play a significant role in corporate operations in the future.

Despite several potential benefits and driving forces, it is important to acknowledge that the value chain actors find it challenging to engage in remanufacturing practices. The key challenges highlighted by the value chain actors are listed in Table 11.

Table 11. Challenges of value chain actors for remanufacturing

Challenges of Remanufacturing	**Company W**	**Company X**	**Company Y**	**Company Z**
Limited collaboration across value chain	✓	✓	✓	✓
Difficulty ensuring quality of remanufactured products	✓		✓	✓
High logistics costs		✓	✓	
Resistance to change	✓			✓
Lack of effective mechanisms	✓			✓
Products not designed for circularity	✓			

First, the major barrier to remanufacturing is due to lack of collaboration among the value chain actors. For remanufacturing to be feasible, it is important that the actors, from original equipment manufacturers to end-customers, share knowledge and information that are relevant to the other actors. Without an enhanced degree of collaboration in the value chain, it is rather difficult to streamline the remanufacturing operations, such as logistics and inventory management. There are several reasons for the limited collaboration in the current value chains. For instance, a interviewee from Company W pointed out that manufacturers are often hesitant to share the product related information because that could 1) jeopardize their business secrets and 2) increase customer’s bargaining power substantially. This further leads to another challenge faced by the remanufacturing companies.

Second, remanufacturers might find it rather difficult to ensure the quality of remanufactured products. The major reason, as emphasized above, is the lack of product traceability across the value chain. It might be rather difficult to evaluate the quality of a component unless its lifecycle information, such as materials used, use conditions, and changes, are accessible. Additionally, the organizations that certify the products’ quality could be hesitant to issue quality certificates for those products that contain reused components. This essence was reflected by Company Z interviewee as:

*“**Storing the recovered components is challenging, but also the quality control**… Getting the CE markings is not that complicated process anymore, but still if you want to use old parts, it becomes tricky. Someone has to check everything, whether they fulfill the requirements of now.” (Company Z)*

Third, if the end-of-life components and remanufactured products need to be shipped across long distances, then the logistics costs can become rather expensive. The interviewee from Company X also pointed out, there is always the risk that logistical expenses cannot be recouped if the returned components do not meet the standards for second life use. The interviewee from Company Y also suggested that, given the high costs of overseas transportation, prices of remanufactured products and new products could become rather comparable.

Fourth, the challenge to remanufacturing also stems from the stakeholders' resistance to adopt remanufacturing practices and the reluctance to invest in necessary technologies. The Company Z interviewee pointed out that not all value chain actors are equally aware or willing to operate in a way that could advance remanufacturing at a systemic level. Additionally, the interviewee acknowledged that the customers tend to resist the purchases of remanufactured products of the quality and value of the products are not communicated properly. The resistance to change in the manufacturing industry was underlined by a Company W interviewee who stated:

*“My observation, manufacturing industry is a very conservative industry and it has high inertia towards changes, because the investment cost for any equipment is quite high. And return on investment depending on what you do, can take quite a bit of time. So, **whenever you are introducing your technology, because of lean mindset, there will be always resistance** in classical places to new solutions...” (Company W)*

Fifth, currently there is still a lack of effective mechanisms to support remanufacturing practices in the manufacturing industry. For instance, an interviewee from Company W stressed that the current legislations lack a clear framework for ensuring lifecycle traceability and reuse of components. Moreover, the Company Z interviewee ascertained that there are not yet standard business models or established business procedures for the trade of reused components. There are currently no widely accepted standards for pricing, quality control, sales, and acquisition of reused components. This is particularly the case if the component recovery business is an independent business entity from the manufacturers or remanufacturers.

Finally, the Company W interviewees emphasized that remanufacturing becomes challenging if the components are not designed with circularity in mind. It was suggested that the products, particularly in the past but even currently, are hardly designed to be dismantled and reused. As a result, it is difficult for the remanufacturers to recover the components intact and prepare them for second life use.

4.4 Perspective of value Chain Actors on Use of DTs for Remanufacturing

4.4.1 Digital Twin

In contrast to BIM in the construction industry, digital twin has not gained widespread acceptance in the manufacturing industry just yet. Thus far, uses of digital twin are mainly limited to manufacturers' internal design and production support. Additionally, it was observed that there are not many instances of digital twins being used to enable component reuse practices. Nevertheless, this study reveals that the digital twin could be a valuable tool in this direction. The perspectives of the value chain actors, on potential digital twin applications for component reuse, are outlined in Table 12 below.

Table 12. Potential uses of digital twin for remanufacturing

Uses of Digital Twin	Company W	Company X	Company Y	Company Z
Beginning-of-life (BoL) information can be stored		✓	✓	✓

Can be connected to IoT gadgets	✓	✓	✓	
Can record product lifecycle information		✓	✓	✓
Supports quality assessment		✓	✓	✓

First, according to the interviewees from companies X, Y, and Z, the digital twin can be used to store various beginning-of-life information of components such as component ID, material composition, physical design, maintenance guide, and end-of-life instructions. Those information are crucial both for maintenance purposes as well as for planning effective remanufacturing decisions such as disassembly procedure, quality assessment, reusability assessment, and preprocessing for second life use.

Second, the digital twin can be connected to IoT gadgets such as RFID tags and sensors that are embedded into the components. This allows that the components are tracked and monitored remotely for the changes in their location, performance, and quality. Consequently, the information gathered by the devices can be automatically pooled into the digital twin and analyzed, which serves several purposes. For instance, the interviewee from Company X emphasized that, based on the information, components can be provided with condition codes which in turn allows the remanufacturer to strategize logistics management, inventory management, and scheduling. Here, condition codes imply a set of distinct codes that are used to differentiate the physical conditions and non-physical associations of different components. Additionally, the interviewee underlined that the lifecycle information can be used for predictive maintenance, thereby, extending the life and reusability of the components. Following comment was made by the interviewee:

*"**If we have digital twin and we can prepare maintenance based on the condition of the core part, we can change the part in right time before it's totally damaged**. Then we get the core in good enough condition that we can remanufacture it... So, it's better for us, better for the customer that we change the part in right time and get the core part in better condition back to us so that we can remanufacture it. Yeah, currently we are developing our preventive maintenance. I think that is big job shift currently and technologies (digital twin, condition coding) helps in this kind of planning a lot." (Company X)*

Third, digital twin can be used as a lifecycle information repository. According to the interviewees from companies X, Y, and Z, digital twin can be used to store historical data about the components, such as usage, performance changes, failures, maintenance history, and parts replacements. When these sorts of information are stored and are accessible to the value chain actors, they can make decisions that directly or indirectly support the remanufacturing. For instance, the Company Y interviewee stressed that the information may be utilized for planning predictive or preventive maintenance, that in turn promotes the component reusability. Additionally, the designers and manufacturers can utilize the information to optimize the design of next generation components so that they are more modular and durable. Most importantly, the historical information stored in the digital twin ensures component traceability for the remanufacturers. Following quote from the interviewee illustrates this notion:

"The target with this remote data is that we basically collect the data and we add in the same system (digital twin) the information of the failed components… ***this is something for preventive maintenance. But it's also affecting whether we service or replace some components before shipping the product to the other customer****. ...***we collect the information on the components what we have installed and we are able to, for example, design new component into our old series, if we see it's required****- i.e., components getting obsolete or there is some problem with the lifetime of the component." (Company Y)*

Finally, remanufacturers can utilize the data from the digital twin to evaluate the quality of end-of-life components, which is essential for deciding whether and how to reuse the components for a second life. As the interviewee from Company Z opined, the EPD data in the digital twin can, in conjunction with other lifecycle information, be used for automated LCA calculation. Moreover, the Company X interviewee stressed the importance of the information in improving component quality so that the performance of the remanufactured products are as good as new ones. On the same line, the interviewee from Company Y mentioned that ensuring the optimal quality of remanufactured products helps the remanufacturer avoid quality correction costs that would otherwise undermine the financial benefits of remanufacturing.

Improvement Areas and Challenges of Digital twin

As mentioned above, this study revealed that the information storage and analysis capabilities are the key factors that justify digital twin use in component reuse context. However, this study also showed that the functionalities and capacities of digital twin still need to be developed further. In this regard, several improvement areas and challenges were recognized. For instance, Company Z interviewee stressed that there not is not yet a standard framework for the data in digital twins. In other words, there is presently no consensus about the types of information that must be recorded, the level of detail required, or the format in which the information should be organized. Additionally, the interviewee from Company Y emphasized that the digital twins currently do not serve as a platform for cross-enterprise information transfer. The interviewee also mentioned that further system development is necessary for digital twin to work with ERP systems and materials management systems.

According to interviewees from Company W and Y, there is varying degree of adoption of digital twin among the stakeholders in manufacturing supply chain. It was inferred by the interviewees that some stakeholders might me more ambiguous than others regarding the value creating potential of the digital twins. Nevertheless, lack of digital twin acceptance across value chain means that more effort is required to gather and update the data into the digital twins. This was reflected by the Company Y interviewee who stated:

*"I would think that **it (digital twin) should be coming to the full manufacturing ecosystem**. It doesn't help so much if we are the only ones who are collecting the information of the components into our system. …**it's not the common standard yet**. So, it's of course challenging, that you need to use a lot of effort to follow the components and collect the information." (Company Y)*

Furthermore, a crucial issue was identified by the Company Z interviewee, who contended that a complete transparency of information through digital twin may not be desirable for all the value chain actors. It is reasonable for the companies to be apprehensive about the possibility that absolute transparency won't compromise their business secrets and bargaining power. However, as the interviewee from Company Y suggested, digital twin technology in the future may be developed in such a way that value chain actors can only access the information in digital twin that are authorized to them.

4.4.2 IoTs

The distinctive characteristic of IoT devices, such as RFID tags and sensors, is their ability to track and monitor products. For this reason, they are often considered significant tools for logistics management, inventory management, and after-sales service support. However, despite their ability to enhance component traceability, adoption of IoT gadgets is not yet prevalent in the component reuse or remanufacturing contexts. It was observed that the value chain actors in this study seldom used IoT gadgets for remanufacturing purposes. Nevertheless, they recognize that the IoT gadgets could be beneficial for the transition towards remanufacturing, and therefore, three potential key applications of IoT gadgets in reuse context were identified, that are listed in Table 13.

Table 13. Potential uses of IoT gadgets for remanufacturing

Uses of IoT	**Company W**	**Company X**	**Company Y**	**Company Z**
Can be attached to components to monitor quality and performance	✓	✓	✓	✓
Can be connected to digital twin or a remote database for recording and updating component lifecycle information	✓	✓	✓	✓
Components can be tagged with corresponding component information	✓			✓

First, IoT gadgets such as RFID tags and sensors can be attached, externally or internally, to the components. This means that the components can be remotely tracked monitored throughout their lifecycle, for gathering the operational data and detecting the changes in performance and quality. This can enable remanufacturing in several ways. For instance, the interviewees from companies W and X emphasize that real-time monitoring of the components allows timely detection of potential failure or breakdowns. In turn, as implied by the interviewees from companies X, Y, and Z, manufacturers or the maintenance providers can schedule predictive maintenance. Though this does not support remanufacturing directly, maintaining the integrity of the components means extending their life and improving their reusability. Additionally, according to the interviewees from companies X and Z, the tracking functionality of the IoT gadgets allows the value chain actors, including remanufacturers, to effectively manage logistics and inventory of both the end-of-life components and remanufactured products. Some of the remarks made by the interviewees are mentioned below:

*“**The machine data we collect can clearly identify if something is going bad**, it’s losing performance, or it’s wearing out.” (Company W)*

*“If we have core condition coding (traceability) in the system, then the system **could make preparations what part we need to have in stock for remanufacturing different cores**. Then we're able to have always right part in stock in the right time.” (Company X)*

Second, the IoT gadgets can be connected to a digital twin or a remote database where the components’ lifecycle information can be automatically recorded and updated. This enhances the visibility over components’ historical information, which supports remanufacturing in variety of ways. For example, the interviewees from companies W and Y highlighted that when components reach end of life, the historical information can be used to assess their remaining life and quality. In turn, remanufacturers can determine the reusability of the components. In addition, access to historical data such as use conditions, maintenance history and changes in performance may be used by the remanufacturers to improve the quality of the remanufactured products. This was emphasized by the Company X and Company Y interviewees as rather important. Those notions are illustrated in following quotes from the interviewees:

*“**We collect background information and the history, then we document them**. So, we know the history of the part when we start remanufacturing it. That **helps us to improve the quality, we know which part must be replaced and so on**.” (Company X)*

*“Every compressor now is part of our remote data collection; we get the operational data from them. **We make sure that the compressor is running in the right conditions, so that we can ensure the lifetime of those components** and we know that we are in the track what we have decided.” (Company Y)*

Finally, with help of IoT gadgets, particularly the RFID tags, components can be tagged with corresponding information. This data-to-tag functionality of IoT was acknowledged by the interviewees from companies W and Z. For instance, an interviewee from Company W suggested that the IoT gadgets with unique ID can be attached to different components, so that when the components are reclaimed by a remanufacturer, it can be known what sort of product they were used in and what functions they had. Additionally, the Company Z interviewee pointed out that component embedded RFID tags can store static information such as component ID, physical characteristics, material compositions, and manufacturing details. These details are crucial for the maintenance operators, but they are more critical for remanufacturers since they aid in quality and lifecycle assessments of the components. In this regard, the Company Z interviewee provided following example:

“For example, a window glass can have RFID codes... You can read what type of glass it is, where it came from, where it was produced. So, ***you don’t need to go to look for any documentation but get the information on your mobile phone or the reader****. If the glass breaks, you can order the same glass pretty quickly… But* ***it relates also to the material passport****. That service is facilitating also the taking back of the glass.” (Company Z)*

As the aforementioned potential applications indicate, IoT gadgets could be conducive to component reuse practices in the manufacturing industry. However, some of the value chain actors in this study acknowledged that use of IoT gadgets is not without challenges. One of the major challenges is the resistance of the stakeholders in implementing the technology. As Company W interviewees suggested, the use cases of IoT gadgets for advancing the component reuse practices are quite new and uncommon, therefore, manufacturing companies might be skeptical about the gadgets’ potential for financial returns and value creation. The interviewee from Company Z pointed out that even though the IoT gadgets may not be very expensive in general, costs might add up when complementary systems such as readers and information management systems are taken into account. Furthermore, the interviewee also mentioned that the manufacturers might be uncertain whether the current IoT technology will still be relevant when the components they are attached to reach end-of-life.

4.4.3 Robotics

Because of robots' potential to automate many operations in the manufacturing and service sectors, they have become widely acknowledged as one of the key technologies in the modern times. However, this study demonstrates that robotics has not gained the same recognition in the remanufacturing context. Though all of the value chain actors in this study were using some kind of robotics automation in the production of new components or product assembly, none were using them to advance the component reuse practices.

It was observed that there is still an ambiguity among the actors whether the robotics automation is suitable and could create any significant value in remanufacturing context. As the interviewee from Company Z pointed out, the current robotics technology needs to be developed further so that they are capable and flexible enough to recover end-of-life components more efficiently. This notion was substantiated also by the interviewees from Company X and Y who emphasized that the key constraining factor for the robotics automation is the variability or unpredictability of end-of-life components in terms of shape, size, mass, and quality. Following remarks from the interviewees illustrate this challenge of adopting robotics in remanufacturing.

*"**It (robotics automation) is a little bit tricky because the condition varies between different core parts**. If you talk about standard manufacturing, it's always the same process because the condition is often the same. But **in remanufacturing, there are different kind of wear and they are on the parts, so there is also variation in the remanufacturing processes**." (Company X)*

*"There are **quite many different parts, different sized, and different weights of the components, so we haven't seen yet possibilities there**." (Company Y)*

*"I guess it's easy to teach some robot, artificial intelligence, to recognize something that's always the same, **but then you are dealing only with one fraction out of the mess (large volume of end-of-life products and components)**." (Company Z)*

4.5 Comparison of DTs Applications in Construction and Manufacturing

This study reveals that there are several similarities between the construction and manufacturing industries in terms of the applications of digital technologies for component reuse. In Table 14, which summarizes the major findings of this study, the similarities and differences between the two industries are highlighted. It was observed in this study that BIM in construction industry is comparable to digital twin in the manufacturing industry. Fundamentally, both BIM and digital twin can act as designing tool and common lifecycle information repository across value chain. Similarly, in both industries, IoT gadgets, such as sensors and RFID tags, can track and monitor the components throughout their lifecycle. The IoT gadgets can also remotely relay the components' historical information to corresponding to BIM model or digital twin. Additionally, RFID tags, in particular, can be used to store some essential information about the components with which they are attached to.

In the similar way that BIM and IoT gadgets are complementary in the construction industry, digital twin and IoT gadgets complement each other in the manufacturing industry. Collectively, these technologies enable gathering, storing, transferring, and analyzing the components' lifecycle information across corresponding value chains. In turn, these technologies facilitate several component reuse practices, such as DfDR, predictive maintenance, logistics and inventory management, quality and lifecycle assessment, and deconstruction or disassembly planning.

Table 14. Synthesis and comparison of findings from construction & manufacturing industries regarding DTs' role in component reuse context.

Digital Technology	Role in Construction Industry	Role in Manufacturing Industry	Other Insights
BIM	- Enables design for deconstruction and reuse (DfDR) - Enables design with reused components (DwRC) - Enables quality and lifecycle assessment - Enables deconstruction planning - Enables creation of digital component library/database	-	- Information (static and historical) is the key to BIM applications in component reuse context. Hence, all actors that possess component related information, designers in particular, need to make sure they record the information into corresponding BIM models. - BIM needs to be developed for platform like functionalities where several actors could collaborate in real time for design works and information sharing. - Construction industry should arrive to a consensus how a standard information format in BIM should be. - BIM should be developed to have a mechanism where information sharing and changes are both safe and transparent. - There is not yet a clear understanding who will own the business that gathers and sells reused component. Though digital component library could be used by such a business, its business model is still lacking.
Digital Twin	-	- Enables design for disassembly and reuse (DfDR) - Enables design optimization - Enables quality and lifecycle assessment - Enables disassembly planning	- Information (static and historical) is the key to digital twin applications in component reuse context. Hence, all actors that possess component related information need to make sure they share and record the information into corresponding digital twin. - Digital twin needs to be developed for platform like functionality that facilitates real time cross-enterprise information transfer. - Manufacturing industry should arrive to a consensus how a standard information format in digital twin should be. - Digital twin should be developed to have a mechanism where information sharing and changes are both safe and transparent. - Though designers and manufacturers are slowly adopting digital twin, the technology diffusion of the digital twin in downstream value chain is still minimal.
IoT (Sensors, RFIDs)	- Enables predictive maintenance - Enables quality and lifecycle assessment - Enables logistics and inventory management	- Enables predictive maintenance - Enables quality and lifecycle assessment - Enables logistics and inventory management - Enables design optimization	- Constructors are yet to recognize the potential of IoT gadgets to enable component reuse. It is critical that they and the building owners recognize it, otherwise it is rather difficult to embed the gadgets into structural components. - For both industries, the IoT gadgets need developed for standardization, durability, and affordability. - In the manufacturing industry, it is critical that the end-users need to be convinced and be provided value in return for components' lifecycle traceability.
Robotics	- Enables partial automation of simple repetitive tasks in deconstruction and second-life preprocessing	(Not yet recognized)	- For robots to be more effective in automating the processes related to component reuse, the designers and manufacturers (in both industry) need to work towards standardizing the components. - Robots should be developed for better flexibility and adaptability to work with components and products of different physical attributes.

Despite the commonalities, a few peculiarities were noticed how the digital technologies can facilitate component reuse in the construction and manufacturing industries. First, the value chain actors in the construction industry emphasized that BIM models of existing components can be utilized by the designers when designing new buildings, such that the new buildings incorporate the existing components. On the contrary, the value chain actors in the manufacturing industry did not consider digital twins of existing components as something that may be utilized when designing new products. Nevertheless, the performance history and quality data of the components, which are collected using IoT devices and stored in a corresponding digital twin, were emphasized by the actors as valuable for optimizing the design of next generation products and components.

Next, whereas the value chain actors in the construction industry surmised the idea of digital component library of existing components, that is, a database where BIM models of existing stock of components are stored. This idea was not acknowledged by the value chain actors in the manufacturing industry. Finally, in the construction industry, robots were acknowledged for partially automating some of the repetitive tasks in component disassembly and second-life processing, such as unfastening nuts and bolts, cutting, and cleaning. However, the use of robots in the component reuse context was not recognized in the manufacturing industry.

In addition to the similarities in how the digital technologies are used, the key issues associated to their usage are also rather similar. This study indicated that both the construction and manufacturing industries have a certain degree of resistance to the adoption of digital technologies. The value chain actors in both industries stressed that for the technologies to be more effective in advancing component reuse practices, their capabilities need to be developed further. Both BIM and digital twin, for instance, need to be developed into collaboratives platforms that allows real-time collaboration among value chain actors. Consequently, several value chain actors may be able to access and update necessary component related information in a single BIM model or Digital twin. However, this necessitates that the BIM models and digital twins have data security mechanisms that protect sensitive information against theft or exploitation. Additionally, the value chain actors in both industries underlined that the robotic systems need to be developed further so that they are flexible enough and effective in handling heterogenous components.

5. DISCUSSION AND CONCLUSION

5.1 Summary of Key Findings

RQ1: What are motivations for component reuse in construction and manufacturing?

As detailed in Chapter 4.1 and Chapter 4.3, the value chain actors in the construction and manufacturing industries have several motivations for component reuse. Incidentally, the key motivations in both the industries are rather common. They include, among others, company's sustainability strategy, increasing customer demand for sustainable solutions, legislative changes, potential supply market disruption, and capitalization on components' residual value. Additionally, in both the industries, some stakeholders are more willing than others to adopt component reuse practices because they intend to gain an experience advantage or the first-mover advantage.

RQ2: What are the challenges of component reuse in construction and manufacturing?

The challenges of component reuse in construction and manufacturing industries were also highlighted in Chapter 4.1 and Chapter 4.3, respectively. While some challenges are specific to each industry, the key challenges faced by both industries are more common than different. In both industries, the major challenges stem from lack of coordination and information sharing across value chain, lack of standard mechanisms for trade of reused components, high logistics costs, disparate standards and legislations across regions, difficulty ensuring the quality of reused components, and stakeholders' resistance to change. Additionally, the existing stock of components in both the industries are difficult to be reused because on one hand, they were not designed with circularity in mind, and on the other hand, there is lack of lifecycle information associated to them. Moreover, peculiar to the construction industry, deconstruction is currently more expensive than demolition.

RQ3: How can the selected Digital technologies (BIM, Digital twin, IoT, and Robotics) enable component reuse practices in construction and manufacturing?

As discussed in Chapter 4.2 and Chapter 4.4, the selected digital technologies advance component reuse in construction and manufacturing in variety of ways. In the construction industry, BIM and IoT gadgets (sensors and RFIDs) allow value chain actors to adopt several component reuse practices, such as design for disassembly and reuse (DfDR), creation of digital component library, design with reused components (DwRC), logistics and inventory management, quality and lifecycle assessment, predictive maintenance, and deconstruction planning. Additionally, robots can facilitate the actual deconstruction process as well as component preprocessing for second life use through partial automation of simple repetitive tasks. Figure 16 illustrates the findings of this study regarding the uses of selected digital technologies to advance component reuse practices in construction industry.

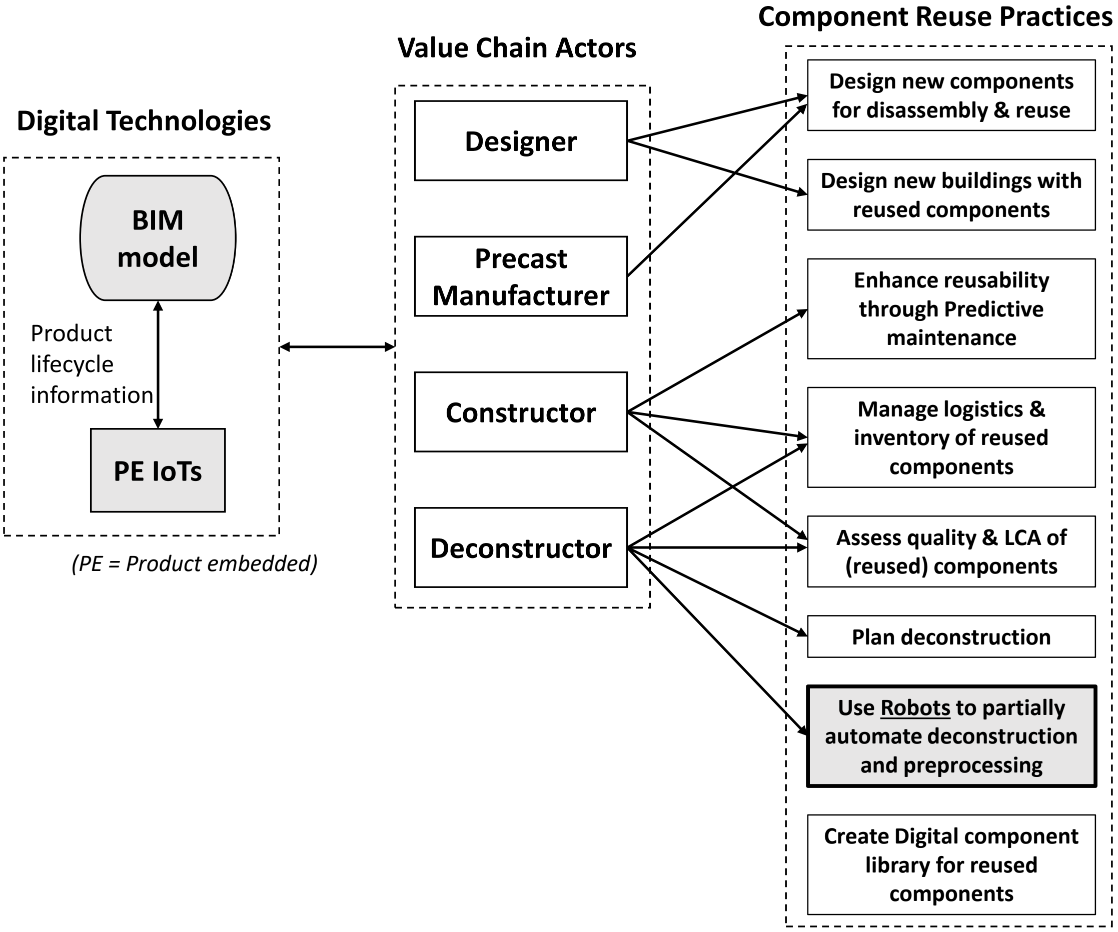

Figure 16. Uses of BIM, IoTs, and Robots for advancing structural component reuse in construction industry.

Similarly, in the manufacturing industry, digital twin and IoT gadgets allow the value chain actors to adopt various component reuse practices – namely, DfDR, design optimization of next generation products, logistics and inventory management, quality and lifecycle assessment, predictive maintenance, and disassembly planning. However, in this study, use of robotics automation was not recognized in component reuse context. Figure 17 depicts the findings of this study regarding the uses of selected digital technologies for advancing component reuse practices in manufacturing industry.

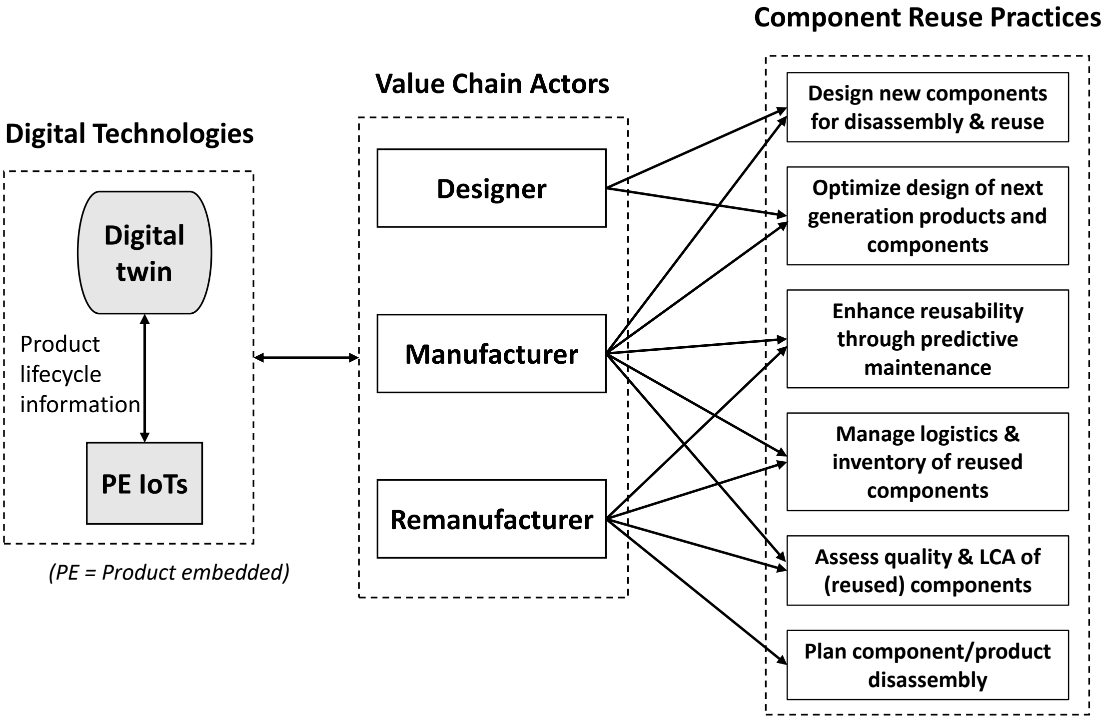

Figure 17. Uses of Digital twin, IoTs, and Robots for advancing remanufacturing.

RQ4: What are the similarities in the use of selected digital technologies for component reuse, between construction and manufacturing?

As described in Chapter 4.5, the construction and manufacturing industries have more similarities than differences in how the selected digital technologies are used for component reuse. BIM and IoT gadgets in construction industry, similar to digital twin and IoT in manufacturing, can enable a number of component reuse practices- namely, DfDR, predictive maintenance, logistics & inventory management, quality & lifecycle assessment, and component disassembly planning. However, peculiar to construction industry, BIM models of existing components can be used as inputs for DwRC and for creating digital component libraries. Similarly, in the manufacturing industry, IoT-provided historical data can facilitate design optimization of the next generation products. Furthermore, the most significant difference between the two industries was observed in terms of robotics automation. Whereas the construction industry seem to recognize the potential of robots to partially automate some simple and repetitive processes during component disassembly and second-life preprocessing, the manufacturing industry is yet to recognize a similar potential.

5.2 Theoretical Contribution

This study contributes to the existing literature on digitalization for circular economy (e.g., Pagoropoulos et al., 2017; Antikainen et al., 2018; Kristoffersen et al., 2020; Ucar et al., 2020; cagno et al., 2021; Laskurain-Iturbe et al., 2021; Chauhan et al., 2022) in several ways. First, in contrast to earlier literature, it takes a broader and integrative approach in understanding the perspectives of multiple value chain actors. On the one hand, this study attempts to understand whether different value chain actors have common motivations and challenges for component reuse. On the other hand, this study attempts to integrate the understandings of different value chain actors on how different digital technologies could advance component reuse practices.

Second, this study validates the previous findings (from, for example, Cruz-Ramirez et al., 2008; Motamedi & Hammad, 2009; Cheng & Ma, 2013; Ness et al., 2015; Bressanelli et al., 2018; Adamu et al., 2020; Xu et al., 2020; Walden et al., 2021) that the digital technologies are de facto the cornerstones of circular economy transition, in both construction and manufacturing industries. The findings confirm that BIM, digital twin, IoT gadgets (sensors and RFID tags), and robots have the potential to advance component reuse practices in variety of ways. Additionally, this study is in line with the previous studies (Iacovidou et al., 2018; Kerin & Pham, 2019; Akberieh et al., 2020; Bertin et al., 2020; Ingemarsdotter et al., 2020; Chen & Huang, 2021) that capabilities of those technologies, particularly the robots (Carra et al., 2018; Sarc et al., 2019; Poschmann et al., 2020), need to be developed further so that they are more effective in facilitating the reuse practices.

Third, this study adds to the literatures a novel finding that the digital technologies are in fact complementary to each other and therefore, their enabling role for component reuse is compounded when used together than separately. This finding directly addresses the research gap pointed out by Liu et al. (2022) that boundaries and synergies between different technologies and their functions need to be explored further. It was observed that sensors and RFID tags can track and monitor the components but they have very little or no data storage capacity. On the other hand, BIM and digital twin can act as data repositories but they do not have the component tracking and monitoring functionalities. In turn, when used together, these technologies can compensate for each other's shortcomings. Similarly, robots can automate certain simple and repetitive tasks, but in order for them to function effectively, their control systems require different component related information. By connecting the robotic control systems to corresponding BIM, digital twin, or IoT gadgets, the robots can automatically access the relevant information.

Finally, to the best of researcher's knowledge, this is first attempt on comparative study of construction and manufacturing industries in terms of how the digital technologies can advance component reuse practices. The findings reveal that the digital technologies play a critical role in both industries and have rather similar applications. Nevertheless, a few differences were identified, that are most likely due to the differences in industry-specific products and business practices.

5.3 Managerial Implications

This study provides a few important practical implications for the managers. First, the findings of this study will help the managers, particularly the sustainability and technology managers, gain a rather comprehensive understanding of digitalization in the context of component reuse. On the one hand, they will be able to assess how the current digital technologies could be employed to maximize the benefits of component reuse. On the other hand, they can evaluate how the technologies need to be developed further to fully realize their potential and enhance their effectiveness. Consequently, the insights from this study enable the managers to create effective digitization initiatives and set reasonable expectations.

Second, this study shows that lack of component standardization limits the feasibility of component reuse, in terms of both economic returns and technology implementation. For instance, due to high variability in shapes, sizes, and quality of components, deconstruction process in construction industry and the remanufacturing process in manufacturing limits the use of robotics automation. In turn, when these processes become rather labor intensive, the economic viability of component reuse may dissipate. Therefore, it is imperative that the component standardization need to be one of the priorities of product designers and product managers in both industries, if they intend to adopt the reuse practices.

Finally, this study establishes to the managers that, like any other circular economy practice, transition towards component reuse necessitates systemic and integrative efforts across the value chain. This means, the managers need to be more open to cross-company collaborations and information sharing. Among others, the sustainability managers, information system managers, and technology developers in both construction and manufacturing industries need to work towards standardization of information formats in BIM and digital twin. In other words, a consensus need to be reached, hopefully with the initiatives from policymakers, regarding what sorts of information are required to be shared and recorded, how detailed the information should be, and how they are organized. However, this also entails that the managers, technology developers, and policymakers need to work on creating effective mechanisms for data and information security.

5.4 Limitations of the Study

As with the majority of research, this study is also subject to limitations. The findings of this study need to be seen in the light of two major limitations. First, the sample size of the study was limited both in terms of numbers and geographical reach. Due to the researcher's restricted access to potential case companies and the time constraint of the research, only a limited number of cases could be accessed, that too, mainly from the Nordic region. This might, to some extent, compromise the generalizability of the findings, particularly for the regions that are beyond the Nordics. However, the researcher acknowledges that the small sample size may not completely undermine the validity of this study because purposive sampling strategy was employed for case selection.

Second, the case companies have not yet fully adopted the digital technologies for the purpose of component reuse. Their perspectives on how the digital technologies advance component reuse practices are, therefore, not entirely based on experiential knowledge. Consequently, the researcher acknowledges that the results of this study are susceptible to interviewee bias. In the future, researchers could employ applied case study approach to either corroborate or refine the findings of this study.

Third, despite this study adopting the value chain perspective, not all value chain actors have been investigated. The researcher acknowledges that the value chain, both in construction and manufacturing, involve several other actors such as maintenance service providers, logistics service providers, and end customers. Though the adoption of the digital technologies could affect all those actors in the value chain, this study opted not to focus on them for the sake of research feasibility and focus. Hence, future research could be even more holistic whereby, the scope of research encompasses the entire value chain.

5.5 Directions for Future Research

Despite the limitations mentioned above, this study identifies several research directions for the future. First, future studies could explore whether and how additional technologies, such as AR, VR, and blockchain, could help enhance the digital technology-enabled component reuse practices identified in this research. For instance, since component reuse practices require increased level of collaboration and information sharing across the value chains, blockchain technology could be studied for its potential to ensure data and information security.

Second, future studies could examine how the information formats in BIM and digital twin could be standardized. This study recognized that lack of standard information formats for BIM and digital twin has been a key barrier to their implementation in the context of component reuse. Therefore, the research in this direction should be the natural extension of current studies.

Third, future research should investigate whether certain technologies could enable quality assessment of components even in the absence of lifecycle information. For instance, technologies such as ground penetrating radar (GPR) could be examined for their ability to assess the quality of concrete elements. Research in this direction could be a valuable contribution because a large portion of currently existing components lack traceability.

Finally, new studies could seek to formulate an effective operating model for a business that garners and sells the end-of-life concrete elements. This study pointed out that such a business could benefit if it creates a digital component library of available components. However, the ownership and business model of the business are still unclear.

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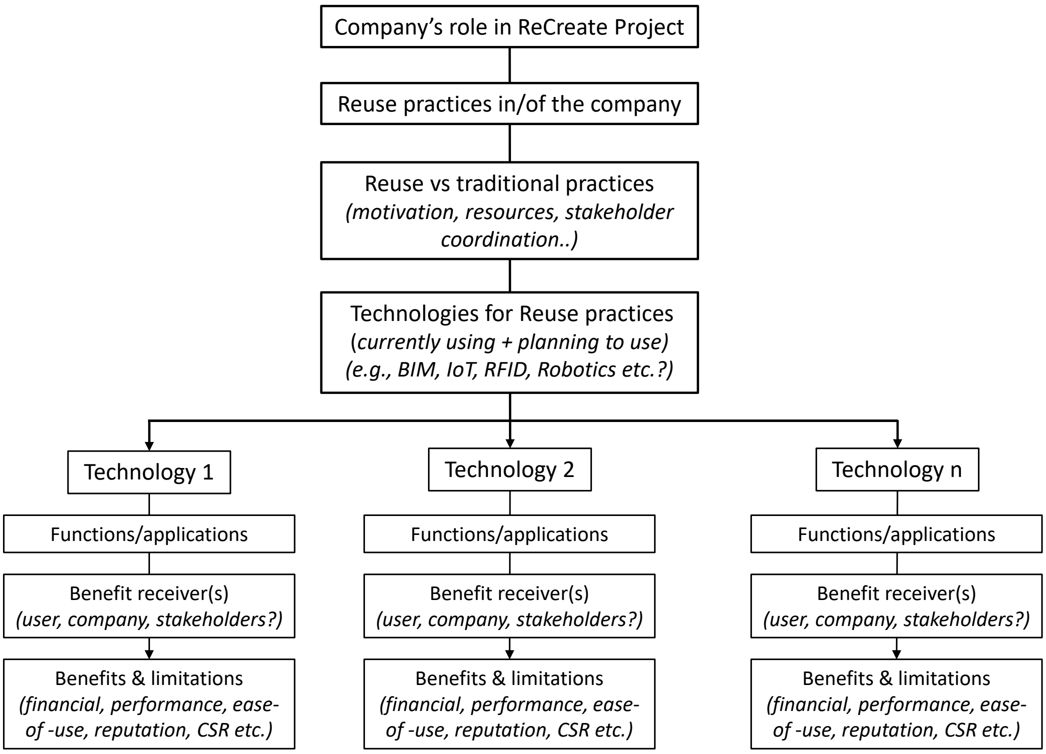
APPENDIX A: INTERVIEW THEMES

Interview Themes for Construction



Interview Themes for Construction