ME6243

Disassembly and Reuse of Demountable Modular Building Systems

Yang Yang[1], Calvin Luk[2], Bowen Zheng[3], Yifei Hu[4], and Albert Ping-Chuen Chan[5]

[1]School of the Built Environment, Oxford Brookes University, Gipsy Lane, Headington, Oxford, U.K. (corresponding author). Email: y.yang@brookes.ac.uk

[2]Jockey Club Design Institute for Social Innovation, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong S.A.R., China. Email: calvin.luk@polyu.edu.hk

[3]Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong S.A.R., China. Email: bowen1999.zheng@connect.polyu.hk

[4] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong S.A.R., China. Email: yi-fei.hu@polyu.edu.hk

[5]Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong S.A.R., China. Email: albert.chan@polyu.edu.hk

Abstract

Numerous efforts have been exerted to explore how modular building systems are built. But limited research has focused on how modular building systems are deconstructed. Deconstruction is a means to systematically disassemble buildings and prioritize building reuse. This paper aims to understand the deconstruction process of modular building systems by providing empirical insights into the disassembly and reuse processes. To achieve this goal, this study employed a mixed-research method, incorporating ethnographic site observations, semi-structured interviews, and archival research, through a case study of a four-story demountable modular building. The empirical findings indicate that the disassembly process consists of a hybrid sequential and parallel disassembly of modular units, while the reuse process consists of four sub-processes: take-back, material tracking, quality inspection, and touch-ups. The contribution of this study to the body of knowledge on deconstruction is twofold: (1) Design for Deconstruction does not inherently ensure effortless ease of disassembly and (2) factors such as client ownership, digital material tracking, and ease of value retention play crucial roles in facilitating building reuse. These findings enhance the understanding of the deconstruction process by addressing the gaps in procurement, information, and quality between the disassembly (the first use cycle) and reuse phases (the second use cycle). By exploring disassembly sequence, take-back mechanisms, technology-driven traceability, and value retention processes, this paper provides valuable support to practitioners transitioning towards the reuse of modular buildings.

Practical Applications

Disassembly and reuse of modular building systems has been practiced less frequently in the construction sector. However, this practice will be in urgent demand given that the increased temporary emergency facilities built around the world will end their service lives in the near future. Consequently, it is essential to understand how modular buildings systems are disassembled and reused, thereby providing valuable references for future deconstruction projects. This research bridges this knowledge gap by providing insights into the issues and facilitators associated with the disassembly and reuse processes of a real demountable modular building. Firstly, the use of bolt and nut connection systems, as one of the Design for Deconstruction principles, allows the separation of one module from another. However, it does not automatically imply the effortless ease of disassembly, as potential lock-in stress of the connections may be present. Secondly, the three facilitators, namely, retained building ownership by the client, digitalized information tracking for individual modules, and ease of repair and replacement of modular components, enable the successful relocation and reuse of disassembled modules. Ultimately, these findings provide construction professionals with useful guidance on better planning and managing the disassembly and reuse processes of similar deconstruction projects in the future.

Keywords: deconstruction, disassembly, relocation, reuse, value retention process, circular economy, Design for Deconstruction

Introduction

Modular construction has been increasingly adopted in response to crises (e.g., earthquakes, pandemic) and the social needs of vulnerable populations (e.g., low-income groups, patients) worldwide, owing to its fast on-site delivery. Examples include the modular construction of hospitals, quarantine centers, and social housing (Chen et al. 2021; Tan et al. 2021; UNECE 2021; Ling 2023). More than 7,000 modular units were built for healthcare facilities in Wuhan, Hong Kong, Shanghai, and Seoul (Construction Industry Council 2020). Moreover, hundreds of prefabricated dwellings, designed to last between 5 to 10 years, were built in Germany and Switzerland for migrants (UNECE 2021). However, if there is a lack of a thoughtful end-of-life planning, most of these temporary modular buildings are likely to be scrapped once people have recovered or transitioned to long-term housing. As a consequence, the disposal of these buildings as demolition waste often results in a greater adverse environmental impact compared to permanent housing (Seike et al. 2018). Therefore, it calls for the adoption of sustainable and circular thinking when these temporary modular buildings are approaching their end-of-services.

In the context of a circular economy (CE), deconstruction plays a crucial role in enhancing the circularity of buildings, as it involves a thoughtful selective demolition of building components (Pantini and Rigamonti 2020). Its primary objective is to maximize the reusability of building parts and minimize demolition waste (Kibert 2003). By prioritizing the preservation of the original physical properties and structural integrity of building parts, deconstruction ensures the highest level of value retention and creation (Munaro et al. 2022). By adhering to the principles of CE, deconstruction extends the lifespan of building components, making it a more sustainable alternative to conventional demolition, where end-of-life construction materials are typically treated as waste with minimal recovery effort.

Guidelines on deconstruction principles have been gradually established since the 1970s, aiming to prolong the functional lifespan of buildings and enhance their reusability (Munaro et al. 2022). Significant process has been made in scientific research on deconstruction, particularly in the fields of design for deconstruction principles (Ottenhaus et al. 2023; Munaro and Tavares 2023; Munaro et al. 2022), methodologies for evaluating deconstructability of buildings (Akinade et al. 2015; Basta et al. 2020; Kim and Kim 2023), and socio-technical conditions for deconstruction (van den Berg et al. 2020). Various technical factors can affect the extent to which a structure can be easily disassembled and reused, including the types of materials used, the mechanisms of wet or dry joints, the methods of construction (on-site or off-site) (Bertino et al. 2021), and quality of future reused elements (van den Berg et al. 2020).

Despite the existence of guidelines on deconstruction principles, only a small fraction, less than 1%, of buildings are completely demountable (Kanters 2018). This is primarily because conventional design approaches do not prioritize ease of disassembly, leading to significant damage to building components and limited potential for reuse once deconstructed. The primary objective of deconstruction is to retain the majority of building parts in their current state and minimize the amount of waste that needs to be recycled, downcycled or landfilled (Akinade et al. 2017; Tatiya et al. 2018). The principle of deconstruction is commonly seen in modular systems, such as mining camps, which are assembled for short-term use before being relocated to the next site (O'Grady et al. 2021a). Similarly, temporary buildings constructed using modular systems in response to emergency or crises, such as earthquakes or pandemics, also adhere to this principle.

Modular building systems that incorporate dry connections can offer high potential for deconstruction. These demountable connections facilitate relatively easy disassembly with minimal damage to modular components, allowing them to retain their original shape or functionality for future reuse (e.g., Sanchez and Haas 2018). A few studies have examined the environmental benefits associated with the reuse of purpose-built modular structures (Minunno et al. 2020; O'Grady et al. 2021a). While several modular building systems claim to be relocatable and reusable, only a few modular buildings have been disassembled, reused, and reinstalled in real-life (Ling 2023). Moreover, the understanding of the deconstruction processes (including disassembly and reuse) in modular systems remains limited, because of the scarcity and fragmented nature of existing studies on deconstruction of modular buildings (Munaro et al. 2022). For instance, van den Berg et al. (2020) is one of the first studies that revealed disassembly routines and documented repair work carried out for the disassembled elements of a reversible modular building system. They further formulated several strategies for increasing the likeliness of the demolition contractor taking a reuse/ recovery decision. It implies that there are uncertainties associated with reuse and the reuse process has not been widely practiced yet (van den Berg et al. 2020). Essentially, the dearth of research and practice on deconstructing modular buildings stresses the need for in-depth investigation and documentation to advance the deconstruction philosophies and improve the understanding of deconstruction practices.

This paper aims to understand the deconstruction process of modular building systems. Specifically, it seeks to provide empirical insights into the disassembly and reuse of demountable modular buildings. By doing so, it contributes to the advancement of deconstruction theories and the improvement of deconstruction practices. This research represents a pioneering study that focuses on the deconstruction process of modular building systems, offering two-fold novelty. Firstly, this paper fills in the knowledge gaps between the processes of disassembly (the first use cycle) and reuse (the second use cycle) in modular buildings, an area that has received limited attention in prior studies (Allam and Nik-Bakht 2023). Secondly, the empirical findings from the deconstruction process validate certain Design for Deconstruction (DfD) principles by examining whether these principles facilitate ease of disassembly. The insights gained from this study can generate new and valuable knowledge in the fields of design and deconstruction of demountable modular buildings. The understanding of the deconstruction process helps shape new practices, serving as a valuable reference of global industry practitioners and policymakers seeking to comprehend the unique considerations associated with deconstruction possibilities. Planners may also have the opportunity to design with foresight, incorporating the deconstruction process into the initial design stage and improving the ease of disassembly and reusability of modular buildings. The improvement in the knowledge on deconstruction ultimately contributes to the transition into a more circular and sustainable future for modular construction. The lessons learned from this study may also generate fresh research ideas and directions for future advancements in disassembling and reusing modular buildings.

The rest of this paper consists of five sections. The first section is a review of deconstruction studies by addressing the critical knowledge gaps in the deconstruction process. Secondly, a mixed-research method, incorporating ethnographic site observations, semi-structured interviews, and archival research, through a case study, is described. Next, empirical findings are presented by identify the key disassembly and reuse processes and sub-processes. Subsequently, key lessons drawn from the findings are discussed, and theoretical and practical implications are offered. Finally, the research novelty, limitations of the study, and future research directions are highlighted.

Literature Review

Deconstruction aims to minimize demolition waste by systematic disassembling buildings to maximize material reuse and recycling (Chini and Bruening 2002; Deniz et al. 2014; Mayer 2017). The deconstruction process primarily comprises disassembly and material recovery. On the one hand, systematic disassembly allows buildings to be disconnected piece-by-piece (Chini and Bruening 2002; Akinade et al. 2017) or layer-by-layer (Crowther 2005; Deniz et al. 2014). Achieving demountability relies on the adoption of DfD principles, such as modularity and dry connections. On the other hand, the primary objective of deconstruction is to maximize the potential for material recovery, including reuse and recycling (Akinade et al. 2017). Building relocation and direct reuse of components and materials are preferable and more sustainable compared to recycling, as they involve minimal reprocessing and downcycling (Crowther 2001; Chini and Bruening 2002; Santos and de Brito 2007; Deniz et al. 2014; Akinade et al. 2017; Allam and Nik-Bakht 2023). Importantly, building reuse represents great challenges (Akinade et al. 2017), while empirical studies on this topic are lacking (O'Grady et al. 2021b). Considering these aspects, the present study investigates the deconstruction process through the lens of disassembly and reuse.

Disassembly Process

The theory of time-related building layers (Brand 1994) emphasizes that a building should not be seen as a single entity but rather a collection of separable layers, each with its own service life, ultimately allowing for the separation of these layers into packages with similar life spans (Crowther 2001). The six primary building layers are stuff, space, services, skin, structure, and site. Consequently, a layer-by-layer approach is commonly employed when dismantling a building. For instance, Mayer (2017) documented the disassembly process of a university facility by removing building skin components, structural elements, and subassemblies in a sequential manner. Santos and de Brito (2007) recorded the disassembly process of a two-story building, starting with the removal of building systems and interior finishing materials, followed by the dismantling of the external envelope, main structure, and foundations. Similarly, van den Berg et al. (2020) described the disassembly process of a temporary nursing home, which involved the gradual removal of interior finishes, fixtures, architectural features, and finally, the disassembly of the framing and removal of the foundation (Denhart 2010). This sequential approach, also known as linear or dependent disassembly, involves removing one part at a time (Sanchez and Haas 2018; Deniz and Dogan 2014). It is adopted because a part can only be disassembled once its connected parts have been disassembled (Sanchez and Haas 2018). In contrast, parallel or independent disassembly is employed when multiple parts can be removed simultaneously due to their independent geometric relationships (Sanchez and Haas 2018; Deniz and Dogan 2014). In determining the disassembly sequence, the geometric relationship and interdependence between a part and its neighboring parts should be taken into consideration (Sanchez and Haas 2018).

The complexity of the disassembly process can be influenced by various factors, such as types and accessibility of connections (van den Berg et al. 2020). Modular building systems, particularly those with demountable and accessible connections, have been recognized as an ideal solution for efficient disassembly and reuse (O'Grady et al. 2021a). Connections using welded joints or in-grout techniques often require destructive disassembly and consequently result in increased damage and decreased reusability. In contrast, dry connections, such as bolted and rivetted joints, facilitate the disassembly of volumetric modules as a whole, minimizing the separation of different building parts and increasing their reusability. Moreover, the accessibility of connections allows laborers to easily reach and utilize hand tools during the disassembly process (O'Grady et al. 2021a; van den Berg et al. 2020). Skilled workmanship and specialized tools can thus provide technical assistance in efficiently disassembling and separating structures into reversible and irreversible component (van den Berg et al. 2020).

Although numerous DfD studies offer a range of dos and don’ts design principles, there is a scarcity of empirical research documenting the integration of these principles into the actual deconstruction process (O’Grady et al. 2021b). While it is widely acknowledged that modular design, lightweight materials, and dry connections facilitate the ease of disassembly for building components, the extent of this ease remains largely unexplored. To shed light on this matter, further exploration is needed to understand the specific deconstruction process employed for demountable modular buildings.

Reuse Process

The main pillars of circular economy (CE) consist of 11 “R” principles: Rethink, Refuse, Reduce, Replace, Repurpose, Remanufacturing, Refurbish, Repair, Reuse, Recover, and Recycle (Çimen 2021). Among these principles, material recycling and energy recovery are given lower priorities in the CE framework, while extending the lifespan of products through value retention processes (VRPs) like repurposing, remanufacturing, refurbishing, repairing, and reusing is considered a higher level of circularity (Franco et al. 2021; Henry et al. 2020) due to their higher value creation and preservation (Henry et al. 2020; Russell and Nasr 2023). Despite these advantages, limited effort has been made to explore how VRPs specifically enable the reuse of buildings.

The “R” principles of a circular economy align closed with waste management hierarchy (Zhang et al. 2022), emphasizing the prioritization of reuse over recycling (Cole et al. 2019). Deconstruction uploads the waste management hierarchy (Akinade et al., 2017) by recognizing that product-level reuse is a more resource-efficient approach and offers better waste prevention compared to recycling (Crowther 2001). Accordingly, the primary objective of deconstruction is to preserve the original properties and structural integrity of building components, ensuring their value is retained through reuse in various contexts (Diyamandoglu and Fortuna 2015; Kibert 2003; Schultmann 2005; Chini and Bruening 2002).

The reuse of building components poses challenges due to uncertainties surrounding both the future scenarios of the building itself (Hossain et al. 2020) and the future performance of disassembled components (van den Berg et al. 2020). Several factors influence the potential for reuse, even when disassembly is feasible (Iacovidou et al. 2021). For instance, the reusability of building components may diminish if those components have experienced decay, deformation, corrosion, or damage (Ottenhaus et al. 2023). The deterioration in quality of these components represents the primary obstacle that hinders their reuse (Anastasiades et al. 2021; Ottenhaus et al. 2023). While proper DfD design can address certain challenges related to ease of disassembly and reusability, the effects of factors, such as the type, duration and direction of loading and climate conditions (moisture content), on the mechanical properties of building components are often underestimated (Ottenhaus et al. 2023). Notably, these effects can vary significantly between different components, even within the same structural system (Ottenhaus et al. 2023). In addition to these technical concerns, van den Berg et al. (2020) has highlighted the critical role played by the availability of transportation, storage, and repair facilities in facilitating the reuse of building elements. While the factors affecting building reuse are well recognized, the actualization of building reuse remains largely unknown, as it is not commonly practiced.

There has been a misunderstanding regarding the direct reuse of disassembled building components in the next cycle even when they have incurred limited damage, as pinpointed by Ottenhaus et al. (2023). This misunderstanding stems from a lack of comprehensive understanding of the entire deconstruction process, from disassembly to reuse. Therefore, there is an urgent need to gain new insights into the complete deconstruction process to bridge the knowledge gap between disassembly (the first use cycle) and reuse (the subsequent life cycles). Consequently, this study aims to understand the deconstruction process of modular building systems. More specifically, the study aims to document the details of the deconstruction process, including disassembly and reuse, and uncover the processes of how modular building systems are disassembled at the end of their first use cycle and subsequently reused in the second cycle.

Methodology

Research Design

The deductive research approach has long been used in construction management to test and validate existing theories and resulting hypotheses through empirical research (Green et al. 2010). In contrast, when it comes to developing new concepts and theories, an inductive approach is usually adopted (Green et al. 2010). This approach involves collecting, observing, and analyzing data to critically question and expand upon traditional theoretical relationships (Tan et al. 2021). Although the theoretical development of deconstruction is still in its early stages, its principles and philosophies cannot solely rely purely on a inductive research process, as they are influenced by the existing theoretical perspectives (Green et al. 2010), such as the theory of building layers and waste management hierarchy (Crowther 2001). To advance the theories related to deconstruction, this research adopts a combined deductive and inductive approach. Such an integrated approach triggers a continuous interplay between existing literature/theories and empirical data (Green et al. 2010), where the exploration and discovery of new knowledge can benefit from theoretical underpinnings (Proudfoot 2023). Specifically, the research begins by testing the established knowledge “deconstructing modular buildings encompasses the processes of disassembly and reuse”. Subsequently, an inductive approach was applied by critically questioning “what are the processes of disassembly and reuse?” This question is formulated based on the argument that deconstruction intends to preserve the value of the disassembled building elements primarily through reuse, as discussed in Literature Review. The research approach adopted not only enables the verification and expansion of traditional theories underpinning the deconstruction process but also enhances the understanding of the new philosophies of deconstruction. **Fig. 1** shows the overall research framework of the study.

<Please insert Fig. 1 here>

Case Study

In this research, a low-rise temporary, demountable, and relocatable social housing project was selected and used to document its deconstruction process and identify the deconstruction principles. This real-life case was chosen because it represents one of the first modular buildings that has successfully executed the full processes of disassembly, relocation, re-assembly, and reuse. Considering the limited availability of deconstruction practices, the selected sole case study could provide unique and empirical insights into the current principles and methodologies (Tan et al. 2024) adopted in the deconstruction process. It would contribute to fostering the transfer of practice into new knowledge, thereby advancing the philosophies of deconstruction. The single case study would offer insightful generalization to theoretical propositions (Yin 2017; Mutikanga et al. 2023; Tan et al. 2024), although its generalizability of findings to future cases (i.e., external validity) is challenged (Hallowell 2012). The background of the case is briefly described below.

Nearly half of the Hong Kong population resides in public housing. As of the third quarter of 2023, the average wait time for public rental housing was 5.6 years (Housing Authority 2024).

Prior to moving into public rental flats, many vulnerable individuals and families have to live for years in tiny, often subdivided, flats. Before the vulnerable can be moved into long-term housing, the provision of short-term accommodation is one of the solutions to improve the quality of life for those vulnerable groups. In the Chief Executive's Policy Address (2021), the provision of transitional housing units was announced to address this pressing social need. Transitional housing refers to the provision of short-term accommodation that facilitate the transition of vulnerable groups into long-term housing (Legislative Council Secretariat 2019). Using the modular construction method to build transitional housing is one of the short-term accommodation options. These modular transitional housing projects are normally built on vacant government-owned or privately-owned land. These projects are called "temporary" because of a restriction to the length of land tenancy under the current transitional housing scheme. The case study presented here is one of the transitional modular housing projects, which was completed in 2020 and subsequently deconstructed in 2023 after a two-year operation period due to the expiration of the land tenancy. Around 35 transitional modular housing projects will probably be relocated in the future (Ling 2023).

The case was a four-story modular building, which consisted of a total of 68 modular units (**Fig. 2**). Each unit was constructed using structural steel frames and precast concrete slabs. All the modular units were dismantled and reassembled in their original configuration at a different location. The inter-module joints were designed using a dry connection mechanism (**Fig. 3**). The disassembly of the modular units started in February 2023. All 68 modular units were removed within three weeks and delivered to a temporary storage yard for inspection and maintenance. All the modular units were reassembled in a new construction site in July 2023.

The modular building has adopted a number of Design of Disassembly, Reuse, and Relocation principles (Crowther 2000). Firstly, modularity enables all interlinked components to be assembled and disassembled (Roberts et al. 2023) in parallel. Secondly, the use of the same type of accessible bolts and nuts inter-module connections not only allows the relative ease of separation but also reduce the complexity of disconnection works (Crowther 2005). Thirdly, steel, as a lightweight material, is used as the primary structural frame, making handling easier and quicker (Crowther 2000). Moreover, a layering approach is adopted to prefabricate each modular unit, allowing the separation of modular parts (Crowther 2000). Last but not the least, material information is traceable in the study project, favoring the option of relocation (Crowther 2000).

<Please insert Fig. 2 here>

<Please insert Fig. 3 here>

Data Collection

This study employed three data collection techniques: (1) ethnographic site observation with short-term passive participation, (2) semi-structured interviews, and (3) archival research. These methods were applied in a single case study depicted above. The research design has been approved by the Human Subjects Ethics Subcommittee of the authors' host university (reference number: HSEARS20211015009).

Ethnographic research offers valuable insights into new construction practices by providing fresh perspectives for practical improvement (Oswald and Dainty 2020). Traditional positivist approaches dominant in the field of construction management (Pink et al. 2010) often struggle to capture the intricate details of "how" practices unfold (Oswald and Dainty 2020). In this context, the adoption of ethnographic research becomes particularly relevant, considering that the selected case involves one of the pioneering instances of fully disassembling, relocating, and reusing demountable modular buildings. By employing ethnographic research, practical challenges on construction sites can be addressed, and new knowledge can be unearthed, as demonstrated by van den Berg et al. (2020) who explored contractors' decision-making on selective demolition. Participant observation serves as the primary method in ethnographic research (Oswald and Dainty 2020). In this study, short-term and passive participation were employed. Short-term observation involved collecting observational data over a period of six months or less (Oswald and Dainty 2020). This approach was suitable in this research because it took roughly six months to execute the entire process of disassembly and reassembly of all modular units (i.e., from February to July 2023). Passive participation entailed observing the site activities without actively engaging in site operations (Oswald and Dainty 2020). In this study, the researchers were passive observers because they were not the registered site personnel and were therefore not permitted to take part in any site activities in compliance with local Construction Site (Safety) Regulations.

In this study, the research team conducted site visits at three distinct locations: Site A, where the modular units were disassembled; Site B, where the modular units were stored, inspected, and repaired; and Site C, where the modular units were reassembled. These site visits were supplemented by the use of photography and video recording (Construction Industry Council 2023), referred to as "auto-ethnography" (Oswald and Dainty 2020). The interdisciplinary research team comprised 13 experts and professionals, including a registered architect, a registered structural engineer, four PhD holders (specializing in construction management, construction economics, and structural engineering, respectively), two research assistants, three photographers, and two industry advisors. During these site visits, the research team documented the activities taking place on-site through written records, photographs, and videos. Site A was visited three times. The research team observed the conditions of the modular building prior to disassembly during the first visit. The second visit focused on the disassembly of the first modular unit. The third visit centered on the disassembly of the final batch of modular units. At Site A, the pre-deconstruction works and the disassembly process were recorded. Site B were also visited three times. The initial visit involved observing the delivery and storage of the first batch of modular units. The second visit focused on observing the maintenance activities carried out at the storage yard. Visual observation was conducted to assess any visible deformations, bulking, and corrosion of modular units. Additionally, the general conditions of fire protection systems, interiors and exteriors of modular units were recorded. During the final visit to Site B, the research team observed the transportation and relocation of the modular units delivered from the storage yard. Site C was visited to observe the reassembly process of the last batch of modular units. The cumulative participant observation time during the disassembly, storage/maintenance, and reassembly phases of the modular building was approximately 190 hours.

Ethnographic research through participant's site observation, however, is challenged by the generalization, validity and reliability of its findings (Phelps and Horman 2010; Oswald and Dainty 2020). It is therefore suggested that site observations should be conducted in combination with other data collection methods, such as interviews, documentary data, and focus groups, in order to complement and cross-validate each other (van den Berg et al. 2020). A semi-structured interview approach was chosen for its ability to combine elements of both the structured and unstructured interview styles, allowing the participant to express their thoughts with some degree of flexibility (Guest et al. 2012). The participants selected for the interview survey were individuals involved in the design, construction, deconstruction, and reassembly phases of the case study. Such a purposive sampling approach was adopted to control the level of variation among the interviewees and enable researchers to meet the goals of the interview (Bazeley 2013) that aimed at exploring the construction, deconstruction, and reassembly processes of modular units. It is worth noting that the contractor responsible for the initial construction did not participate in the deconstruction and re-assembly processes. Instead, the structural engineering consultant appointed by the client was involved in all phases.

Therefore, four representatives from the consultant, including the Director and three structural engineers, were invited to participate in the interview survey as they were the key participants in the case study. Previous studies involved a limited number of interviewees in their single case studies (e.g., two safety managers in Martinez et al. 2020, and four experts in Al-Mhdawi et al. 2022). Despite a limited sample size, the study adopted a mixed research method that consisted of ethnographic research, archival research, and interview survey to cross-validate the findings of each other. The primary interview questions focused on three main topics: (1) validating the reusability of modular units assessed by the authors and (2) explaining the processes of construction, deconstruction, and reassembly of modular units. The duration of the interview was approximately 60 min.

Unpublished in-house documents were requested from interviewees, including a demolition plan, a logistics plan, a condition survey report, a structural appraisal report, a mark-up plan, and a reassembly plan, to obtain details of the disassembly and reuse processes. Specifically, the demolition plan documented the demolition sequence of the modular building, the removal sequence of module connections, design drawings of a layout plan and module connections, a lifting plan, and safety precautions adopted during the disassembly process. This demolition plan was reviewed to understand the sequence of disconnecting inter-module connections and the sequence of removing modular units. The design drawings of module connections were used to produce 3D diagrams in the study. The lifting plan showed the deployment of a crane during the disassembly process by indicating the crane type, number of workers engaged, and the designated working zone. The demolition plan and the lifting plan were used to develop a schematic diagram about the disassembly process of modular units in this paper. The safety plan presented safety measures implemented before and during the disassembly process, including the erection of temporary hording and crane outrigger pads. Such information was collected to understand the implementation of safety measures during the disassembly process.

The logistics plan documented the schedule of delivery of dissembled modular units from Site A to Site B. It was obtained to estimate the approximate duration of the disassembly process (i.e., three weeks). The condition survey report and structural appraisal report were collected to understand the methodology and the process of quality inspection of modular units. Correspondingly, the mark-up plan was obtained to indicate the specific replacement of fire sealants and gemtree boards required by each modular unit. The reassembly plan was gathered to comprehend the reassembly sequence of modular units. These archived documents serve to validate and substantiate the insights obtained through the interview process (Green et al., 2010) and the site observations carried out by the authors.

Data Analysis

Prior to carrying out qualitative data analysis, various forms of data were documented, including written records, interview scripts, archives, and the research team's reflections on the photos and videos captured during the site visits. Specifically, the research team regularly held internal meetings to discuss the implications of the visual materials and written diaries recorded during site observations. For instance, a photo showing surface rust on a steel member of a ground-floor modular unit suggested that ground moisture could be a contributing factor. All of these records were treated as raw data, representing the unprocessed information collected for further content analysis. A preliminary coding of raw data was conducted by assigning semantic meaning to one or more sentences or graphs (Thompson 2022). For example, a preliminary code assigned to the aforementioned photo was "ground-floor moisture leading to surface rust". These preliminary codes were listed and used for either consolidation or categorization in the following content analysis.

In order to validate the established knowledge, a deductive content analysis was performed to answer the specific question: how is the deconstruction process, encompassing the disassembly and reuse processes in existing literature, identified in the case study? To achieve this, a predetermined coding scheme was developed based on existing theory, which was used to categorize the raw data (Spearing et al. 2022). Specifically, the preliminary coding scheme consisted of a set of codes, such as disassembly process and reuse process.

To address the second research question regarding the processes of disassembly and reuse, both deductive and inductive content analytic techniques were used. This process involved examining both existing knowledge and emerging insights from the case study (Spearing et al. 2022). Specifically, the second research question could be further refined as follows: "how well do the existing disassembly process describe the case study experience?" and "what are the newly identified reuse processes from the case study?" A deductive coding approach was employed to address the first sub-question. By stemming from the existing literature, the predefined coding scheme was designed for detailing the disassembly process, encompassing codes such as disassembly sequence, disconnecting bolts and nuts joints, and dismantling modules. Then an inductive coding approach was applied to address the second sub-question. Specifically, the open coding approach was used to analyze the transcripts by extracting and segmenting key ideas or concepts, categorizing them into (sub)themes, and summarizing the contextual information (Spearing et al. 2022). As a result, additional themes, stemming from the empirical observations, were incorporated into the coding scheme, namely, reverse logistic process and value retention process, which served as sub-themes under the main theme of reuse process. As the open coding process continued, further new themes were identified, including take-back mechanism and traceability under the sub-theme of reverse logistics, and quality inspection and touch-ups under the sub-theme of value retention. Intercoder reliability was ensured through independent coding by two coders until consensus was reached on all the codes (Spearing et al. 2022).

Following the theme development, an abductive reasoning approach was applied to theorize data. Specifically, the study examined all possible theoretical explanations for the themes (Thompson 2022; Charmaz 2006; Tavory and Timmermans 2014) by comparing the themes with literature. For instance, the deconstruction theories of time-based building layering and waste hierarchy and DfD principles were used to interpret the deconstruction process. Then the study examined instances for which themes could not be interpreted by existing literature (Thompson 2022; Tavory and Timmermans 2014). For example, the existing deconstruction theories and DfD principles failed to explain to what extend the ease of disassembly would be. The iterative engagement with theory and empirical data can trigger theoretical developments by either refining, changing, adapting, or consolidating theory (Thompson 2022; Green et al. 2010).

Results

This section presents the findings of ethnographic research, semi-structured interview, archival research of a case study. The results identify three primary processes and six sub-processes associated with the deconstruction of a demountable modular building system. **Table 1** summarizes the key findings originated from corresponding sources.

<Please insert Table 1 here>

Disassembly Process

Disconnecting Joints

The sequence of dismantling the modular building system consisted of the following major steps, i.e., removing or disconnecting internal and external building service systems, removing interior finishes located between adjacent modules, disconnecting joints, and dismantling modules. This sequence is viewed as a sequential approach where one building part is removed at a time (Santos and de Brito 2007; Sanchez and Haas 2018).

Firstly, the interior and exterior mechanical, electrical, and plumbing (MEP) equipment were either removed or disconnected. Secondly, specific interior finishes, such as floor and wall coverings and ceiling finishes, located between adjacent modules, were partially removed. This step aimed to expose the inter-module connections, enabling workers to easily access them during the disassembly process (O'Grady et al. 2021a). While the modular buildings were designed to be reversible structures, certain components had connections that were irreversible or inaccessible (van den Berg et al. 2020). For instance, the on-site tie-ins, such as power lines and plumbing, were removed forcefully and thus, they were not reusable and disposed of.

After removing MEP equipment and interior finishes, the third step was to disconnect the modular units by loosening the inter-module connections that held the adjacent four modules. The accessibility issue was solved through an opening in the wall panel and thus the inter-module connection could be accessed from the interior. Moreover, the design of the modular units allowed the direct exposure and accessibility of the inter-module joints from the exterior of the module. The inter-module connection comprised one T-section, two tie plates, two steel tubes, and bolts and nuts. Initially, the T-section and upper and lower tie plates were loosened by removing the bolts and nuts. Subsequently, the upper module was removed, and then the steel tube connecting the upper and lower adjacent modules were dismantled. The disconnection of inter-module connections (**Fig. 4**) can be viewed as a reverse process of their initial connection, where the adjacent four modules were first connected by inserting the steel tubes into steel hollow sections of each modular unit and subsequently securing them with the T-section and tie plates by using bolts and nuts (**Fig. 5**).

<Please insert Fig. 4 here>

<Please insert Fig. 5 here>

According to the DfD principles, bolts and nuts connections could facilitate the easy separation of modular components (Kitayama and Iuorio 2023). However, the findings of this study revealed that disconnecting bolts and nuts joints was not as straightforward as anticipated. It is worth noting that these connections were designed to provide structural rigidity, resulting in tightly connected bolts and nuts (which implies structural integrity). It was also observed that the steel tubes were tightly inserted, suggesting the presence of potential lock-in stress caused by permanent load. In such cases, workers had to use a handy tool to tap the steel tube or the hollow section, releasing the lock-in stress. The disconnection of bolts and nuts joints still necessitates quality craftsmanship and hands-on skills of workers.

Disassembling Modular Units

The disassembly process of the modular units was carried out in a zone-by-zone manner. Within each zone (**Fig. 6**), the modular units on the upper floors were removed first, followed by those on the lower floors. It is viewed as a sequential disassembly because the disassembly of the lower-floor modular unit requires the disassembly of the upper box concerning their dependent geometric relationship. This sequence was also determined due to the congested site conditions, where only one traffic pathway allowed the operation of a mobile crane. The zone-by-zone assembly sequence had also been adopted during the initial construction, which was necessitated by site constraints. Thus, the disassembly sequence can be seen as a reverse of the assembly sequence. Since each modular unit consists of structure, skin, services, and fit-out layers, removing a modular unit, also known as volumetric disassembly (Rausch et al. 2017), can also be regarded as a parallel disassembly when multiple parts are removed at the same time (Sanchez and Haas 2018; Deniz and Dogan 2014). Therefore, the disassembly sequence of the modular building is a combination of sequential and parallel modes.

<Please insert Fig. 6 here>

As each modular unit was lifted, it was then placed on a 12-meter-long truck. A total of four riggers and one crane operator were engaged to dismantle and position the modular unit to the truck. The 68 modular units were removed within three weeks. Once all modular units were transported to the storage yard, they were laid flat to undergo inspection and maintenance to ensure their structural integrity. The disassembled modular units were placed in and delivered from the storage yard following the rules of "first-in, last-out" (upper floor) and "last-in, first-out" (lower floor). This arrangement facilitated the reassembly process when the modular units were transported to the new project site, ensuring that they were assembled in the correct sequence.

Concerning varying dead load spread on different modular units, it was restricted to reinstall the modular units as their original configuration. As a result, the modular units were reused in the same building system, probably limiting their interchangeability, flexibility and adaptability. It is worth noting that the reassembly sequence adopted a floor-by-floor manner. The modular units on the lower floors were reassembled, followed by those on the upper floors. This approach was used because there was ample space available, allowing the mobile crane to move around. Generally, the floor-by-floor assembly/disassembly sequence may offer better structural stability compared to the zone-by-zone approach. This is because in the floor-by-floor sequence, the load is transferred linearly and distributed evenly, whereas the zone-by-zone sequence may induce angled load paths through the entire structure. For instance, when removing the modules in zone 3 adjacent those in zone 4, safety measures were implemented to ensure that the modular units in zone 4 would not topple or collapse by enclosing the lifting zone and installing temporary support. This is because the pyramid-like structure of zone 4 might have a higher center of gravity, making it more vulnerable to instability and tipping over if it is not adequately supported. The present findings suggest that the sequence of removing modular "boxes" should be determined in a safe manner that ensures the structural integrity of the remaining parts throughout the disassembly process.

Reverse Logistics

Take-back Mechanism

It was found that the public client appointed a design-build contractor to handle the disassembly, transportation, refurbishment, and re-assembly of the original modular building on a new site. It is important to note that this contractor was not engaged in the design, manufacture and assembly of the original modular building. The disassembly and reassembly works were not initially considered in the prior design-build procurement. At the end of service life of the modular building, the client initiated an open tendering process to procure a suitable contractor who could handle both the deconstruction (i.e., disassembly, maintenance, and reassembly) of the original building and the design and construction of new modular buildings. A new contractor was thus selected through open-tendering to ensure transparency, accountability, and public interest, avoiding potential biased negotiations with the original contractor engaged in public projects. This procurement method proved that the used building products were not necessarily returned to the original contractor. Instead, they were taken back by a new contractor who was responsible for the entire deconstruction process, including disassembly, maintenance/repair, and reassembly, regardless of whether they were involved in the initial assembly or not. Essentially, the ownership of the modular building remains with the same public client throughout both the initial and subsequent use cycles. Therefore, the client could be able to provide the deconstruction contractor with necessary specifications of the original modular design and material information as the deconstruction contractor needs to understand the connection design and replaceable materials.

Traceability

To ensure the accurate reassembly of each modular unit in its original configuration, a unique quick response (QR) code was assigned to each modular unit enabling tracking and locating throughout disassembly, transport, and re-assembly. The QR code contains essential information about each modular unit, including dimension, floor location, dates and times of disassembly, delivery, and reassembly, as well as details of the crane and truck used. On-site engineers could easily access module information by scanning the QR codes, which greatly assisted in tracking the entire deconstruction process, identifying the location of each modular unit, and improving the efficiency of the reassembly process. However, a few limitations of the QR code system deployed were observed. The use of two A4 papers to display QR codes on the front surface and inner side of each modular unit has proven problematic, as these papers are easily damaged or lost. One potential solution could be to engrave the QR codes directly onto the interior and exterior surfaces of the modular units. However, this approach may influence the finishes and overall appearance of the decorations. Moreover, the QR codes could become blurred due to occupants' interactions, as noted by a site engineer. Furthermore, there might be potential security risks associated with the existing QR codes, as unauthorized individuals could be able to scan and access them and modify the information. The third limitation of the current QR code system lies in its limited scope of providing basic information about the modular units and the deconstruction processes, while detailed information about inspection and refurbishment of the modular units was not recorded.

Value Retention

Quality Inspection

A three-stage inspection process was implemented to assure the quality of the reused modular units. Specifically, the first stage involved conducting a condition survey of the modular units prior to disassembly. Based on the archival information obtained from interviewees, no structural abnormalities such as cracking or deformation were observed, indicating that the interior and exterior of the modular units were in good condition. During the second stage, a condition survey was conducted immediately after the modular units were disassembled. The exterior and interior sides of each module were extensively photographed, resulting in more than 500 photos that were submitted for inspection, comments, and approval by relevant statutory authorities. The inspection survey revealed that the conditions of the modular units before and after disassembly remained largely unchanged, indicating no visible damage or deflection during the disassembly process. As a result, it was determined that structural members were in good condition and were reusable. The condition surveys conducted both before and after disassembly relied primarily on visual observation, which could be time-consuming and subjective as it heavily relies on the judgement of inspectors (Xu and Yang 2020; Yeum and Dyke 2015).

The first two quality inspection procedures were employed to determine the suitability of the modular units for direct reuse, the need for repairs or refurbishment, or the complete rejection of reuse, whereas the third stage aimed to assure the quality of modular units before reuse. In the third stage of inspection, a detailed structural appraisal was conducted after the touch-ups and before the reassembly of the modular units. The sampling size of 10%, which equated to 7 modules out of a total of 68, were chosen for structural appraisal, although scientific evidence supporting the chosen sampling approach is limited. The structural appraisal encompassed a series of non-destructive tests, including dimensional measurement, coating thickness measurement, and weld test. Dimensional measurements in length, height, and width of the exposed steel members were carried out. The test results were compared to the approved design to determine whether there exist significant differences in sectional dimensions and thickness (i.e., >1mm). As a result, it was concluded that the tested members were examined without significant deformation. The thickness of the galvanized coating and fire protection painting on the exposed steel members was also measured. The measured coating thickness of the surveyed steel members either matched or exceeded the approved thickness, indicating enhanced fire resistance and anti-corrosion protection. Furthermore, magnetic particle test was performed to detect surface or near-surface flaws in welded column to beam joints. The results indicated that no defects were found in the welded joints, affirming the reusability of the column to beam joints in the modular units.

Touch-ups

Touch-ups plays a crucial role in ensuring the reusability of modular components, enabling their continued use in subsequent service life cycles. Upon the two years of use, module joints and exposed steel structural members were found in good condition, exhibiting no significant deformation, bending, or damage. However, slight surface rusts were observed in a few steel components. For instance, slight surface rusting was observed on the back of a T-section over the inter-module connections. The rust stain could be attributed to water accumulation in the gaps between the T-section and the steel columns, potentially leading to surface corrosion. Localized surface rusting was observed near the beam-column joints of a specific module (label

2-3-1, **Fig. 6**). This was likely caused by prolonged water presence in the gaps between adjacent modules. Additionally, surface rust stains were found on a steel column of a top-floor unit (label 3-1-5, **Fig. 6**), possibly resulting from rainwater ingress. Furthermore, surface rusting was detected on a steel beam of a ground-floor module (label G-2-5, **Fig. 6**), likely due to exposure to ground moisture. Minor surface rust stains were detected on a top cover panel of a specific second-floor unit labelled as 2-1-1 shown in **Fig. 6**. The rust stain likely resulted from rain ingress through the gap between the second and third floor modules. In three modular units, the fireproof painting had peeled off from the steel members, potentially resulting from scratches during assembly or disassembly. To address these issues, touch-ups were performed by removing rust stains and repainting the affected connections and steel members. Protective zinc coating and fireproofing coating were applied to ensure enhanced protection against corrosion and fire hazards. Fire sealants and gemtree boards were also replaced to ensure the continued effectiveness of the fire protection system for subsequent use. A small number of wall and floor tiles in a toilet showed signs of cracking and peeling due to normal wear and tear. These tiles were subsequently removed and replaced.

Discussion

This section discusses the key lessons derived from the aforementioned deconstruction process of a modular building system by uncovering that (1) DfD does not inherently ensure effortless ease of disassembly and (2) factors such as client ownership, digital material tracking, and ease of value retention play crucial roles in facilitating building reuse.

Ease of Disassembly

It has been widely recognized that modular design, lightweight materials, and dry connections enable ease of disassembly of building components. While the current empirical findings support the use of these DfD principles, it is important to note that modularity and dry connections do not guarantee effortless ease of disassembly. The empirical findings offer new insights into the effectiveness and practicality of DfD principles.

Bolts and Nuts Joints

The utilization of bolts and nuts joints to enable damage-free dismantling of building components is widely acknowledged. However, limited studies have empirically substantiated the ease of disassembly achieved through the use of bolts and nuts joints in real deconstruction projects. A common misconception arises when it is assumed that bolts and nuts joints automatically guarantee effortless easy disassembly. In the current case, the bolts and nuts connections were designed to facilitate the detachment of modular units without causing structural damage. However, the on-site observations revealed that the disconnection of inter-module joints using bolts and nuts did not guarantee effortless results due to potential lock-in stress. Thus, workers had to manually release the lock-in stress, highlighting the demanding nature of manual handling during the systematic disassembly process (Akinade et al. 2017; Allam and Nik-Bakht 2023; van den Berg et al. 2020). Surprisingly, there is a lack of research addressing the issue of lock-in stress associated with bolts and nuts connections. This indicates the necessity for further advancements in DfD connections that not only prioritize structural integrity but also facilitate easier disconnection by minimizing the reliance on manual handling during the disassembly process.

Furthermore, it is crucial to consider that the modular building examined in this research had a relatively short operational period of just two years. If the building's operational lifespan is extended, there could be additional uncertainties arising from dead loading effects, increased lock-in stress, and the degradation of building conditions resulting from occupants' use over time. Therefore, it is vital to recognize that factors such as the duration of use, type and direction of loading, and prevailing climate conditions can potentially impact the ease of disassembly and reassembly (Ottenhaus et al. 2023). Future studies are recommended to explore different types of DfD joints and assess the influence of loading and climate conditions on both the ease of disassembly and reuse. The adoption of innovative technologies, such as automated (dis)connecting device (Picard et al. 2024), may enhance the precise of (dis)assembly and thus reduce the reliance on manual handling. Additionally, it is advised to validate the present findings when alternative module connection systems are used.

Disassembly Sequence

Previous research has examined either sequential (Sanchez and Haas 2018) or parallel (Sanchez et al. 2019) approaches to disassembling building parts. In the current case study, a hybrid approach combining sequential and parallel disassembly methods was observed. The removal process followed a sequential order for internal and external building service systems, interior finishes located between adjacent modules, bolts and nuts connections, and modular units. This sequential approach was necessary as the modules could not be disassembled if the interconnected components (such as power lines and flooring between adjoining modules) were not disconnected.

Regarding the disassembly of modular units, a sequential approach was adopted, where one unit was removed at a time. However, it is important to note that the modular design allowed certain building layers (such as structure, skin, services, space, and stuff) to be constructed as a single unit and removed together. This approach can be seen as a form of parallel disassembly, as it minimizes the separation of different layers and reduces the risk of damage. The findings emphasize the importance of incorporating modularity into DfD principles. The modular design enables the parallel disassembly of individual modular units, potentially reducing disassembly time and cost (Smith and Hung 2015) compared to a sequential method.

Given that the modular building was only operated for two years, it was still technically reusable until it would reach its end of life. When the modular building system reaches the end of its life, it becomes essential to investigate the disassembly process of each modular unit as its disassembly method may be different with that for demounting modular boxes. Van den Berg (2020) documented a sequential disassembly routine for disassembling a temporary modular building that ends of its service life. While non-destructive disassembly was employed to recover the modular façade, destructive disassembly had to be used deconstruct ceiling tiles and floor slabs (van den Berg et al. 2020). Similarly, it is anticipated that destructive disassembly would likely be necessary for the current individual modular units because dismantling welded steel beams and columns in each unit could cause structural damage and increase the complexity of the disassembly process. Future research is recommended to explore systematic disassembly approaches for individual modular units that have reached the end of their lives. This should consider the interdependence of components, as well as the residual environmental and economic value, to determine which parts should be recovered and which should be disposed of (Sanchez and Haas 2018).

Linkage between disassembly and reuse

A misunderstanding arises from the assumption that demountable components are inherently reusable, as indicated by Ottenhaus et al. (2023). To clear up this misconception, the present empirical findings suggest that client ownership, digital material tracking, and ease of value retention are essential for bridging the gaps in procurement, information, and quality between disassembly and reuse.

Client Ownership

The study uncovered that the disassembly and repair of modular units were carried out by a new contractor who was not involved in the initial construction phase. However, the ownership of the modular building remained with the same public client throughout both the initial and subsequent use cycles. This finding has significant implications. Firstly, the successful implementation of the innovative take-back mechanism relies on the continuity of ownership for the modular building. With unchanged ownership, the client can reuse the modular units in future projects since finding a new client willing to use secondary building products can be uncertain. This continuity of ownership helps address concerns about potential economic losses (Anastasiades et al. 2021) due to limited market demand for secondary building parts. By retaining ownership, the client assumes responsibility for promoting the reuse of the modular building in subsequent use cycles. Building on past practical experience, it has been demonstrated that minimizing changes in client ownership is an effective approach to ensuring the feasibility of material reuse (Big Buyers Initiative 2020). This is particularly relevant for city building agencies that aim to utilize building materials in their own renovation and construction projects (Big Buyers Initiative 2020).

Secondly, the retention of client ownership sets it apart from conventional take-back mechanisms like Extended Producer Responsibility (EPR). ERP emphasizes that suppliers bear responsibility for their services throughout the entire lifecycle of the building (Charef et al. 2022). Under EPR, it is envisioned that when a product reaches the end of its lifecycle, the client returns salvaged building components to the contractor, supplier, or manufacturer who then take on the responsibility of promoting disassembly and reuse instead of disposal. While this product as service model has been implemented in a few public projects (e.g., Brummen Town Hall in the Netherlands, Jones et al. 2017), the demand for the reuse of secondary building parts remains uncertain. Building components differ from typical consumer products, as potential new clients may exhibit hesitancy in purchasing secondary building parts due to concerns regarding quality, remaining lifespan, hidden risks, and liability. Given these hurdles of implementing producer responsibility, the present study implies the feasibility of client ownership in promoting building reuse.

There are potential risks of significant damage occurring during the stages of use, lifting, and transport. It is crucial for the client and the new contractor to establish an emergency plan to sourcing replaceable modular units in such cases. While approaching the original contractor for replacements is a possibility, conflicts may arise due to intellectual property rights associated with the design of modular joints, leading to complex contractual relationships between the client and the contractors involved. On the other hand, producing new replacements by a new contractor may be an alternative, but the economic viability of manufacturing a few modular units relative to creating a new mould can pose challenges for both the client and the contractor. Concerning the potential risks of unexpected damage to modular units, it appears that EPR may be a more viable option, as the original contractor can be responsible for repairing and replacing damaged components with predetermined charges. However, the consideration of EPR should occur during the early procurement phase of the primary construction. The uncertain financial and contractual risks associated with implementing EPR for a whole building have not been explored yet.

In the present case study, the client re-tendered the deconstruction works as the original Design-Build procurement did not take deconstruction into account. It is recommended that a whole-life-cycle approach, such as the Design-Build-Deconstruction procurement (Yang et al. 2022), be considered for future projects involving demountable and reusable buildings, although this new approach has not yet been tested. In such cases, scenarios for the second use cycle should be planned early, considering the uncertainties that significantly challenge the client.

There is ongoing debate regarding ownership and take-back mechanism for building reuse, particularly as project delivery methods have not been established for deconstruction projects (Allam and Nik-Bakht 2023). Future studies are needed to systematically identify the financial and contractual risks associated with different ownership models and take-back mechanisms in building reuse.

Digital Material Tracking

One of the key principles that enables building relocation and reuse is maintaining comprehensive information about the building's manufacturing, assembly, disassembly processes, material and component life expectancy, and maintenance requirements (Crowther 2000). The case study adopted a digital solution to track modular units, which provide traceability for reusable building parts by collecting and sharing data (Giovanardi et al. 2023) across multiple use cycles. It further enhances transparency of the overall deconstruction processes (Zhai et al. 2019) and establishes trust and collaboration among different stakeholders involved in the project (Ellsworth-Krebs et al. 2022).

To address the limitations of the existing QR code system in terms of limited data information and potential security issues, future research directions are offered to achieve traceability and transparency of building information throughout the entire deconstruction process. Firstly, to address this issue and improve information security and data protection, the implementation of disruptive technologies like blockchain has been suggested (Yu et al. 2022; Li et al. 2022). Blockchain technology can enhance security, especially when more detailed data such as supplier information, reusability records, and inspection reports are recommended to be included. Secondly, the QR code system can be further expanded with various scales, including (i) material-scale information, e.g., origin, supplier, specification, and certificate, (ii) component-scale information, e.g., connection design, designed service of life, reusability, inspection records, and refurbishment records, (iii) modular unit-scale data, e.g., configuration, weight, size, and embodied carbon, and (iv) process-scale data, e.g., dates and time of disassembly, delivery, refurbishment and re-assembly, and disassembly sequence. Given the potential for multiple reuse cycles and the involvement of various contractors in (de)construction of modular units, it becomes crucial to collect, store, share, analyze, and manage life cycle data on modular units over time. Contractors who were not involved in the initial design and construction stages can access the QR code system to understand the material lifespan and disassembly sequence. Furthermore, they could follow the designated maintenance instructions to procure appropriate replacement materials and carry out necessary maintenance.

Ease of Value Retention

VRPs have generally been overlooked during building deconstruction. This research represents a pioneering study that emphasizes the importance of value retention during the building deconstruction process. Some studies have incorporated VRPs in their life cycle assessments of building component reuse, suggesting that demountable building components may not be suitable for direct reuse in the next cycle without prior VRPs (van Stijn et al. 2021; Yang et al. 2024). These processes, along with quality inspection, are essential for ensuring that modular units can be reused in the second use cycle. In the present study, the deteriorated lifespans of building components typically resulted from material degradation, manual handling, and improper occupant behaviors. The lifespans of building components can further influence the type and intensity of VRPs, such as repair, replacement, and refurbishment (van Stijn et al., 2021).

By differentiating between "product core" (Krystofik et al. 2018; Goodall et al. 2014) and non-core components of a modular building system (Yang et al. 2024), it is recognized that certain non-core components with shorter life expectancies require more extensive replacement due to faster degradation from wear and tear (IRP 2018) compared to product cores with longer life expectancies. For example, the steel frame, as the core structure of the modular system, was reused after minor repairs, such as applying protective zinc and fireproofing coating. Non-core components like fire sealants, gemtree boards, and a few wall and floor tiles were replaced due to their shorter lifespans. In the long term, non-core components such as bolts and nuts joints may require extensive replacement when the frequent loosening and fastening of connections during the disassembly and reassembly processes result in decreased joint strength. Interior refurbishment may also be intensive due to the longer use period and possible improper occupant behaviors.

The successful implementation of various VRPs for core and non-core components relies on their independent geometric relationship. The separation of non-core components from the core structure allows for the replacement of non-core components without affecting the core structure. Instead of discarding the entire modular unit, the separation of the damaged non-core part from the core structure enables the implementation of VRPs targeting the damaged part without compromising the lifespan of the core structure. Consequently, the entire modular unit could be continuously used. This finding implies that the adoption of building layering design not only allows for the separation of building layers (Crowther 2001) but also facilitates the ease of repair and replacement of less durable non-core components (Crowther 2000).

Theoretical and Practical Implications

This paper contributes to the existing body of knowledge on deconstruction by offering empirical insights into the deconstruction process of a low-rise modular building. Theoretically, this study is pioneering in its investigation of the disassembly and reuse processes in a modular building project, which bridges the knowledge gaps that exist between these two processes. Additionally, this paper validates certain DfD principles that either fully or partially enable ease of disassembly and reuse. In terms of practical implications, managerial approaches such as procurement innovation and technology innovation play an important role in building reuse. The lessons learned from deconstructing demountable modular buildings can help construction professionals better respond to similar deconstruction projects in the future.

Specifically, the studied modular building system is demountable due to the adoption of several DfD principles, including modular construction, bolts and nuts connections, lightweight materials, and building layering approach. While these principles enable the disassembly of the modular building system, the ease of disassembly is not inherently guaranteed due to potential lock-in stress of bolts and nuts joints. This finding has three implications. Firstly, it provides valuable information for industry practitioners to improve planning and management of manual handling, equipment, tools, and craftmanship to release the lock-stress of the connections during the disassembly process. Secondly, it highlights a misunderstanding in existing DfD principles, where the use of bolts and nuts joints is mistakenly assumed to automatically guarantee ease of disassembly without considering potential lock-in stress of the connections. Previous studies have failed to fully comprehend the practicality of DfD principles due to a lack of empirical research or insufficient integration of feasible DfD principles into practice. Lastly, the finding suggests the need for an in-depth investigation of various DfD connections and assessment of their potential lock-in stress, which may hinder ease of disassembly.

Another misconception that is clarified is the assumption that demountable components are automatically reusable. By uncovering the disassembly and reuse processes, this paper fills a gap in the procurement of building reuse. The introduction of a novel take-back mechanism with client ownership offers fresh insight into how building reuse can be procured in public projects. This new circular business model, characterized by client ownership and the return of products to a new contractor, exemplifies the application of circular economy principles in practice, as the owner and contractor adapt their business models to this new paradigm. Moreover, a technology-driven material tracking system that provides important information repository is essential for effective deconstruction planning, management, and execution. By bridging the information gap between disassembly and reuse, this digital tracking system can be improved and implemented in future deconstruction projects to facilitate the exchange of information between successive use cycles. Furthermore, the quality gap between successive use cycles is a major concern in building reuse. VRPs play a crucial role in repairing and replacing obsolete components and refurbishing the building to a new state. The adopted building layering approach facilitates the ease of value retention by separating obsolete components from the modular frame and replacing them with new ones. To conclude, the findings of this paper bridge the procurement, information, and quality gaps between disassembly and reuse, making a theoretical contribution to the existing knowledge on deconstruction. These valuable lessons can guide construction professionals in better planning and managing similar deconstruction projects in the future.

Concluding Remarks

There has been an increasing trend in the provision of low-rise temporary, demountable, and relocatable modular building systems in light of the pressing need for emergency facilities worldwide due to their fast on-site delivery. These buildings often fulfill their intended purpose before reaching the end of their designed service lives. Disassembling and reusing these facilities can help preserve their value in the economy and align with the principles of sustainability and the circular economy. This empirical study presents a pioneering and detailed examination of the deconstruction process of a low-rise demountable modular building system, showcasing its successful disassembly, relocation, and reuse in real-life scenarios.

Regarding the deconstruction process, the empirical findings indicate that the disassembly process involves a hybrid sequential and parallel disassembly of modular units, while the reuse process consists of four sub-processes: take-back, material tracking, quality inspection, and touch-ups. Based on these findings, the study contributes to the existing knowledge on deconstruction by revealing that (1) DfD does not inherently ensure effortless ease of disassembly and (2) factors such as client ownership, digital material tracking, and ease of value retention play crucial roles in facilitating building reuse. These new empirical findings provide a deeper understanding of the deconstruction process by bridging the procurement, information, and quality gaps between disassembly (the first use cycle) and reuse (the second use cycle).

Moreover, this research has significant practical implications. The exploration of factors such as ease of disassembly, take-back mechanisms, technology-driven traceability, and ease of value retention offers a systematic approach for practitioners involved in deconstruction projects. The identified processes and factors that link disassembly and reuse should be carefully considered to enable multiple reuse cycles, ultimately supporting the transition towards circular reuse of modular buildings.

However, it is important to acknowledge some limitations that may hinder the broader application of deconstruction. The implications of this study may not directly apply to projects that have not incorporated DfD principles, as they may involve different disassembly and reuse processes. The results may also be specific to low-rise temporary and demountable buildings, which represent a particular type of construction typology. Furthermore, due to the limitations of a single case study in terms of external validity, further empirical studies are needed to validate the present findings by comparing similar or different construction typologies (e.g., high-rise demountable modular buildings) and enrich the existing knowledge on building deconstruction. Additionally, a comprehensive understanding of the deconstruction process, which enables both reuse and recycling, should be investigated, considering that not all building parts are reusable.

Based on the above findings, future research can focus on two primary domains. Firstly, structural engineering research should be conducted to develop easily demountable and interchangeable modular systems and understand the influences of various loading conditions, duration, climate factors, and the frequency of assembly and disassembly on disassembly performance and reusability. Secondly, engineering management research is needed to address key issues that can bridge the gaps between disassembly and reuse. This includes exploring contractual and financial risks in procuring deconstruction projects, technological advancements in material tracking, and the development of disassembly methodologies for obsolete modular units.

Data availability statement

Some data (i.e., interview scripts and records, photos, and videos of site observations) that support the findings of this study are available from the corresponding author upon reasonable request. Some data (i.e., a demolition plan, a logistics plan, a condition survey report, a structural appraisal report, a mark-up plan, and a reassembly plan) used during the study are proprietary or confidential in nature and may only be provided with restrictions. Restrictions are applied to the availability of these archival research data if the participants of the study give written consent for their data to be shared publicly.

Acknowledgements

This paper forms part of the research projects funded by the Construction Industry Council of Hong Kong S.A.R., and the General Research Fund (No. 15221722), the Research Grant Council of Hong Kong S.A.R., from which other deliverables will be produced with different objectives/scopes/methodology but sharing common background and findings of the case study. The Housing Bureau of Hong Kong S.A.R., Wilson & Associates Ltd., Woon Lee Construction Co., Ltd., CNQC International Holdings Limited., CNQC Intelligent Construction (Hong Kong) Limited, who contributed their time and knowledge are greatly acknowledged. We also thank editors and anonymous reviewers for their constructive comments.

References:

Akinade, O. O., L. O. Oyedele, M. Bilal, S. O. Ajayi, H. A. Owolabi, H. A. Alaka, and S. A. Bello. 2015. “Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS).” *Resour. Conserv. Recycl.* 105, 167-176.

Akinade, O. O., L. O. Oyedele, S. O. Ajayi, M. Bilal, H. A. Alaka, H. A. Owolabi, S. A. Bello, B. J. Jaiyeoba, and K. O. Kadiri. 2017. “Design for deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills.” *Waste Manage.* 60, 3-13.

Al-Mhdawi, M. K. S., M. P. Brito, M. Abdul Nabi, I. H. El-Adaway, and B. S. Onggo. 2022. "Capturing the impact of COVID-19 on construction projects in developing countries: A case study of Iraq." *J. Mange. Eng.* 38(1), 05021015.

Allam, A. S., and M. Nik-Bakht. 2023. "From demolition to deconstruction of the built environment: A synthesis of the literature." *J. Build. Eng.* 64, 105679.

Anastasiades, K., J. Goffin, M. Rinke, M. Buyle, A. Audenaert, and J. Blom. 2021. "Standardisation: An essential enabler for the circular reuse of construction components? A trajectory for a cleaner European construction industry." *J. Clean. Prod.* 298, 126864.

Basta, A., M. H. Serror, and M. Marzouk. 2020. "A BIM-based framework for quantitative assessment of steel structure deconstructability." *Auto. Constr.* 111, 103064.

Bazeley, P. 2013. *Qualitative data analysis: Practical strategies*. Los Angeles, CA: Sage.

Bertino, G., J. Kisser, J. Zeilinger, G. Langergraber, T. Fischer, and D. Österreicher. 2021. "Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials." *Appl. Sci.* 11(3), 939.

Big Buyers Initiative. 2020. *Public procurement of circular construction materials: key takeaways from the Big Buyers Initiative working group*. ICLEI – Local Governments for Sustainability, European Secretariat.

Brand, S. 1994. *How buildings learn*. Viking, New York.

Charef, R., W. Lu, and D. Hall. 2022. "The transition to the circular economy of the construction industry: Insights into sustainable approaches to improve the understanding." *J. Clean. Prod.* 364, 132421.

Charmaz, K. 2006. *Constructing grounded theory: A practical guide through qualitative analysis*. London: SAGE.

Chen, L.K., R.P. Yuan, X.J. Ji, X.Y. Lu, J. Xiao, J.B. Tao, X. Kang, X. Li, Z.H. He, S. Quan, and L.Z. Jiang. 2021. "Modular composite building in urgent emergency engineering projects: A case study of accelerated design and construction of Wuhan Thunder God Mountain hospital to COVID-19 pandemic." *Auto. Constr.* 124, 103555.

Chief Executive's Policy Address. 2021. *Policy Address*. Available at: https://www.policyaddress.gov.hk/2021/eng/policy.html. Accessed on 13 Oct. 2021.

Chini, A. R., and S. Bruening. 2002. "Design for deconstruction and materials reuse CIB task group 39 - deconstruction meeting CIB." In *International Council for Research and Innovation in Building Construction Task Group 39: Deconstruction*. Karlsruhe, Germany.

Construction Industry Council. 2020. MiC projects. https://mic.cic.hk/en/MicProjects (accessed on 7 Oct. 2021).

Construction Industry Council. 2023. *Technical Report on the Deconstruction, Relocation and Reinstallation of MiC modules in Nam Cheong 220 Transitional Housing Project*. Authors: Luk, C., Y. Yang, K. F. Chung, *et al.* 31 Oct. 2023. https://mic.cic.hk/en/Publications (accessed on 15 Jun. 2024).

Çimen, Ö. 2021. "Construction and built environment in circular economy: A comprehensive literature review." *J. Clean. Prod.* 305, 127180.

Cole, C., A. Gnanapragasam, T. Cooper, and J. Singh. 2019. "An assessment of achievements of the WEEE Directive in promoting movement up the waste hierarchy: experiences in the UK." *Waste Manage.* 87, 417-427.

Crowther, P. 2000. "Developing guidelines for designing for deconstruction." In *Deconstruction-Closing the Loop Conference Proceedings*. Building Research Council.

Crowther, P. 2001. “Developing an inclusive model for design for deconstruction.” In *Proc., the CIB Task Group 39-Deconstruction Meeting*, 1-26. Wellington, New Zealand.

Crowther, P. 2005. “Design for disassembly–themes and principles”. *Environ Design Guide*. v. 2, p. 1–7.

Denhart, H. 2010. “Deconstructing disaster: Economic and environmental impacts of deconstruction in post-Katrina New Orleans.” *Resour. Conserv. Recycl.* 54(3), 194-204.

Deniz, O. S., and E. Dogan. 2014. “Building façade system for deconstruction.” *J. Sustain. Archit. Civil Eng.* 8(3), 59-74.

Diyamandoglu, V., and L. M. Fortuna. 2015. “Deconstruction of wood-framed houses: Material recovery and environmental impact.” *Resour. Conserv. Recycl.* 100, 21-30.

Ellsworth-Krebs, K., C. Rampen, E. Rogers, L. Dudley, and L. Wishart. 2022. “Circular economy infrastructure: Why we need track and trace for reusable packaging.” *Sustain. Prod. Consum.* 29, 249-258.

Franco, N. G., M. F. L. Almeida, and R. F. Calili. 2021. “A strategic measurement framework to monitor and evaluate circularity performance in organizations from a transition perspective.” *Sustain. Prod. Consum.* 27, 1165-1182.

Giovanardi, M., T. Konstantinou, R. Pollo, and T. Klein. 2023. “Internet of Things for building façade traceability: A theoretical framework to enable circular economy through life-cycle information flows.” *J. Clean. Prod.* 382, 135261.

Goodall, P., E. Rosamond, and J. Harding. 2014. “A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility.” *J. Clean. Prod.* 81, 1-15.

Green, S. D., C. C. Kao, and G. D. Larsen. 2010. “Contextualist research: Iterating between methods while following an empirically grounded approach.” *J. Constr. Eng. Manage.* 136(1), 117-126.

Guest, G., E. E. Namey, M.L. Mitchell. 2012. *Collecting qualitative data: A field manual for applied research*. Sage: Thousand Oaks, CA, USA.

Hallowell, M. R. 2012. “Safety-knowledge management in American construction organizations.” *J. Manage. Eng.* 28(2), 203-211.

Henry, M., T. Bauwens, M. Hekkert, and J. Kirchherr. 2020. “A typology of circular start-ups: An Analysis of 128 circular business models.” *J. Clean. Prod.* 245, 118528.

Hossain, M. U., S. T. Ng, P. Antwi-Afari, and B. Amor. 2020. “Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction.” *Renew. Sustain. Energy Rev.* 130, 109948.

Housing Authority. 2024. *Number of applications and average waiting time for public rental housing*. Available at: https://www.housingauthority.gov.hk/en/about-us/publications-and-statistics/prh-applications-average-waiting-time/. Accessed on 18 Feb. 2024.

Iacovidou, E., P. Purnell, K. D. Tsavdaridis, and K. Poologanathan. 2021. “Digitally enabled modular construction for promoting modular components reuse: A UK view.” *J. Build. Eng.* 42, 102820.

Johnson, T.R., and J. F. Krems. 2001. “Use of current explanations of multicausal abductive reasoning.” *Cogn. Sci.* 25(6), 903-939.

Jones, M., I. K. Sohn, and A.L. Bendsen. 2017. *Circular procurement case study collection*. ICLEI – Local Governments for Sustainability, European Secretariat.

IRP. 2018. “Re-defining value – The manufacturing revolution, remanufacturing, refurbishment, repair and direct reuse in the circular economy.” by N. Nasr, J. Russell, S. Bringezu, S. Hellweg, B. Hilton, C. Kreiss, and N. von Gries. A Report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

Kanters, J. 2018. “Design for deconstruction in the design process: State of the art.” *Buildings*. 8(11), 150.

Kibert, C. J. 2003. “Deconstruction: the start of a sustainable materials strategy for the built environment.” *Ind. Environ.* 26(2), 84-88.

Kim, S., and S. A. Kim. 2023. “A design support tool based on building information modeling for design for deconstruction: A graph-based deconstructability assessment approach.” *J. Clean. Prod.* 383, 135343.

Kitayama, S., and O. Iuorio. 2023. “Disassembly and reuse of structural members in steel-framed buildings: State-of-the-art review of connection systems and future research trends.” *J. Arch. Eng.* 29(4), 03123006.

Krystofik, M., A. Luccitti, K. Parnell, and M. Thurston. 2018. “Adaptive remanufacturing for multiple lifecycles: A case study in office furniture.” *Resour. Conserv. Recycl.* 135, 14-23.

Lawson, R. M., S. O. Popo-Ola, A. Way, T. Heatley, and R. Pedreschi. 2010. “Durability of light steel framing in residential applications.” In *Proc., The Institution of Civil Engineers-Construction Materials*. 163(2), 109-121.

Legislative Council Secretariat. 2019. *Fact sheet- transitional housing in selected places*. Available at: https://www.legco.gov.hk/research-publications/english/1819fs06-transitional-housing-in-selected-places-20190218-e.pdf. Accessed on 10 Otc. 2021.

Li, X., W. Lu, F. Xue, L. Wu, R. Zhao, J. Lou, and J. Xu. 2022. “Blockchain-enabled IoT-BIM platform for supply chain management in modular construction.” *J. Constr. Eng. Manage.* 148(2), 04021195.

Ling K. K. 2023. *Study on effective transitional housing delivery in Hong Kong: report on policy recommendations*. Available at: https://www.polyu.edu.hk/publications/pulse-polyu/issue/202308/spotlight-on/jcdisi-releases-interim-findings-from-study-on-effective-transitional-housing-delivery-in-hong-kong. Accessed on 18 Dec. 2023.

Martinez, J. G., M. Gheisari, and L. F. Alarcón. 2020. UAV integration in current construction safety planning and monitoring processes: Case study of a high-rise building construction project in Chile. *J. Manage. Eng.* 36(3), 05020005.

Mayer, M. 2017. “Diversion dynamics: A process-based approach to deconstruction analysis.” In *Proc., 105th ACSA Annual Meeting*. May 2017. ACSA Press.

Minunno, R., T. O’Grady, G. M. Morrison, and R. L. Gruner. 2020. “Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building.” *Resour. Conserv. Recycl.* 160, 104855.

Munaro, M. R., S. F. Tavares, and L. Bragança. 2022. “The Ecodesign methodologies to achieve buildings’ deconstruction: A review and framework.” *Sustain. Prod. Consum.* 30, 566-583.

Mutikanga, H. E., M. Kayondo, and C. S. Akita. 2023. “Performance of Chinese international contractors in sub-Saharan Africa: Evidence from Uganda.” *J. Manage. Eng.* 39(3), 05023003.

Ottenhaus, L. M., Z. Yan, R. Brandner, P. Leardini, G. Fink, and R. Jockwer. 2023. “Design for adaptability, disassembly and reuse–A review of reversible timber connection systems.” Constr. Build. Mater. 400, 132823.

O’Grady, T., R. Minunno, H. Y. Chong, and G. M. Morrison. 2021a. “Design for disassembly, deconstruction and resilience: A circular economy index for the built environment.” *Resour. Conserv. Recycl.* 175, 105847.

O’Grady, T. M., R. Minunno, H. Y. Chong, and G. M. Morrison. 2021b. “Interconnections: An analysis of disassemblable building connection systems towards a circular economy.” *Buildings*. 11(11), 535.

Oswald, D., and A. Dainty. 2020. “Ethnographic research in the construction industry: a critical review.” *J. Constr. Eng. Manage.* 146(10), 03120003.

Pantini, S., and L. Rigamonti. 2020. “Is selective demolition always a sustainable choice?” *Waste Manage.* 103, 169-176.

Picard, L., P. Blanchet, and A. Bégin-Drolet. 2024. “On-site handling: Automated connecting device for modular construction used as lifting apparatus.” *Structures*. 63, 106318.

Phelps, A. F., and M. J. Horman. 2010. “Ethnographic theory-building research in construction.” *J. Constr. Eng. Manage.* 136(1), 58-65.

Pink, S., D. Tutt, A. Dainty, and A. Gibb. 2010. “Ethnographic methodologies for construction research: knowing, practice and interventions.” *Build. Res. Inform.* 38(6), 647-659.

Proudfoot, K. 2023. “Inductive/deductive hybrid thematic analysis in mixed methods research.” *J. Mix. Methods Res.* 17(3), 308-326.

Rausch, C., M. Nahangi, M. Perreault, C. T. Haas, and J. West. 2017. “Optimum assembly planning for modular construction components.” *J. Comput. Civ. Eng*. 31(1), 04016039.

Roberts, M., S. Allen, J. Clarke, J. Searle, and D. Coley. 2023. “Understanding the global warming potential of circular design strategies: Life cycle assessment of a design-for-disassembly building.” *Sustain. Prod. Consum.* 37, 331-343.

Russell, J., and N. Nasr. 2020. “Value retention processes within the circular economy.” In: *Remanufacturing in circular economy*. Nasr, N. (ed.). 2nd edition. Scrivener Publishing, Beverly, USA.

Russell, J. D., and N. Z. Nasr. 2023. “Value-retained vs. impacts avoided: the differentiated contributions of remanufacturing, refurbishment, repair, and reuse within a circular economy.” *J. Remanuf.* 13(1), 25-51.

Sanchez, B., and C. Haas. 2018. “A novel selective disassembly sequence planning method for adaptive reuse of buildings.” *J. Clean. Prod.* 183, 998-1010.

Sanchez, B., C. Rausch, and C. Haas. 2019. “Deconstruction programming for adaptive reuse of buildings.” *Auto. Constr.* 107, 102921.

Santos, A., and J. de Brito. 2007. “Building deconstruction in Portugal: a case study.” In *Proc., Portugal SB07 Conference—sustainable construction, materials and practices—challenge of the industry for the new millennium*. 1059-1066.

Schultmann, F. 2005. “Sustainable deconstruction of buildings.” *Smart Sustain. Built Environ.* 148-159.

Seike, T., Y. Kim, Y. Hosaka, S. Ida, and T. Masuda 2018. “Intraregional reuse of emergency temporary housing in Japan.” *Sustain. Cities Soc.* 42, 650-662.

Smith, S., and P. Y. Hung. 2015. “A novel selective parallel disassembly planning method for green design.” *J. Eng. Design.* 26(10-12), 283-301.

Spearing, L. A., A. Bakchan, L. C. Hamlet, K. K. Stephens, J. A. Kaminsky, and K. M. Faust. 2022. “Comparing qualitative analysis techniques for construction engineering and management research: The case of Arctic water infrastructure.” *J. Constr. Eng. Manage.* 148(7), 04022058.

Tan, T., G. Mills, J. Hu, and E. Papadonikolaki. 2021. “Integrated approaches to design for manufacture and assembly: A case study of Huoshenshan hospital to combat COVID-19 in Wuhan, China.” *J. Manage. Eng.* 37(6), 05021007.

Tan, T., G. Mills, and E. Papadonikolaki. 2024. “Exploring multidimensional modularity: Strategies to reduce complexity in design activities.” *J. Manage. Eng.* 40(3), 05024002.

Tatiya, A., D. Zhao, M. Syal, G. H. Berghorn, and R. LaMore. 2018. “Cost prediction model for building deconstruction in urban areas.” *J. Clean. Prod.* 195, 1572-1580.

Tavory, I., and S. Timmermans. 2014. *Abductive analysis: Theorizing qualitative research*. University of Chicago Press.

Thompson, J. 2022. “A guide to abductive thematic analysis.” *Qual. Report*. 27(5), 1410-1421.

UNECE (United Nations Economic Commission for Europe). 2021. *Housing for migrants and refugees in the UNECE region challenges and practices*.

van den Berg, M., H. Voordijk, and A. Adriaanse. 2020. “Recovering building elements for reuse (or not)–Ethnographic insights into selective demolition practices”. *J. Clean. Prod.* 256, 120332.

van Stijn, A., L. M. Eberhardt, B. W. Jansen, and A. Meijer. 2021. “A circular economy life cycle assessment (CE-LCA) model for building components.” *Resour. Conserv. Recycl.* 174, 105683.

Xu, X., and H. Yang. 2020. “Vision measurement of tunnel structures with robust modelling and deep learning algorithms.” *Sensors*. 20(17), 4945.

Yeum, C. M., and S. J. Dyke. 2015. “Vision-based automated crack detection for bridge inspection.” *Comput.-Aided Civ. Infrastruct. Eng*. 30(10), 759-770.

Yang, Y., J. Guan, J. M. Nwaogu, A. P. Chan, H. L. Chi, and C. W. Luk. 2022. “Attaining higher levels of circularity in construction: Scientometric review and cross-industry exploration.” *J. Clean. Prod*. 375, 133934.

Yang, Y., B. Zheng, C. Luk, K. F. Yuen, and A. Chan. 2024. “Towards a sustainable circular economy: Understanding the environmental credits and loads of reusing modular building components from a multi-use cycle perspective.” *Sustain. Prod. Consum*. 46, 543-558.

Yin, R. K. 2017. *Case study research and applications: Design and methods*. Thousand Oaks, CA: SAGE

Yu, Y., D. M. Yazan, V. Junjan, and M. E. Iacob. 2022. “Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies.” *J. Clean. Prod.* 349, 131335.

Zhai, Y., K. Chen, J. X. Zhou, J. Cao, Z. Lyu, X. Jin, G.Q.P. Shen, W. Lu, G. Q. Huang. 2019. “An Internet of Things-enabled BIM platform for modular integrated construction: A case study in Hong Kong.” *Adv. Eng. Inform.* 42, 100997.

Zhang, C., M. Hu, F. Di Maio, B. Sprecher, X. Yang, and A. Tukker. 2022. “An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe.” *Sci. Total Environ.* 803, 149892.

Fig. 1. Research framework

Fig. 2. Schematic diagram of the modular building Note: The BIM was developed by the authors based on the 2D drawings shared by the interviewees

Fig. 3. Design of bolts and nuts connection Note: The 3D connection configuration was produced by the authors based on the 2D and 3D drawings shared by the interviewees

Fig. 4. Disconnection of inter-module joints Note: The 3D disconnection configuration was produced by the authors based on the 2D and 3D drawings shared by the interviewees

Fig. 5. Connection of inter-module joints Note: The 3D connection configuration was produced by the authors based on the 2D and 3D drawings shared by the interviewees

Fig. 6. The disassembly sequence (adapted from Construction Industry Council 2023)

Note: Each of 68 modular units was assigned with a unique label. For each label, the first character represents the story, the second character represents the zone, and the third character represents the sequential number of each modular unit per floor

Table 1. Key findings of the case study

Deconstruction process	Deconstruction sub-process	Key findings	Sources
Disassembly	Disconnecting joints	Bolts and nuts disconnection but lock-in stress requires manual handling	Site observation, interview, archival research
	Disassembly of modules	Hybrid sequential and parallel disassembly sequence	Site observation, interview, archival research
Reverse logistics	Take-back mechanism	Client ownership, Novel take-back mechanism	Interview
	Traceability	QR code used to track modular units, Tracible disassembly and reuse processes but limitations are observed	Site observation
Value retention	Quality inspection	Three-stage quality inspection before and after disassembly and before reassembly	Site observation, archival research
	Touch-ups	Removing rust stains and applying protective zinc coating and fireproofing coating on the affected connections and steel members, Replacing deteriorated fire sealants and gemtree boards, Replacing deteriorated wall and floor tiles	Site observation, interview, archival research