



Optimal multi-use cycle scenarios for temporary demountable modular building systems: An environmental sustainability perspective

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ABSTRACT

Currently, there is limited understanding of how many years and how many times demountable modular building systems can be reused while remaining minimal adverse environmental impacts from a multi-use cycle perspective. This study aims to identify optimal multi-use cycle scenarios for a demountable modular unit that achieves minimal environmental impacts. Multi-objective optimization was conducted to determine the optimal number of use cycles and the duration of each cycle, focusing on minimizing both environmental cost and residual value. Six Pareto-optimal scenarios were identified to minimize both the environmental cost of embodied and operational carbon emissions and residual value. They are [5-yr, 5-yr], [5-yr, 25-yr], [10-yr, 25-yr], [15-yr, 25-yr], [20-yr, 25-yr], and [25-yr, 25-yr], implying that the optimal number of use cycles is two. The finding serves as valuable insight for developing end-of-life planning strategies that promote the sustainable reuse of demountable modular building systems.

1. Background

Modular construction has been increasingly adopted in response to crises, such as earthquakes and pandemics, as well as to address the social needs of vulnerable populations, including low-income groups, patients and disaster victims. Temporary modular building systems have been developed worldwide for hospital facilities, quarantine centres, social care facilities, social housing, and emergency shelters (Chen et al., 2021; Local Government Association, 2021; Tan et al., 2021; UNECE, 2021; Clough, 2022; European Union, 2022). In Germany and Switzerland, hundreds of prefabricated dwellings for migrants have been built, with lifespans typically ranging from 5 to 10 years (UNECE, 2021). In the UK, temporary modular solutions have been proposed to alleviate pressure on hospital facilities (National Health Service, 2024). In Hong Kong, temporary modular transitional housing projects have been built on vacant lands to meet the needs of vulnerable households before their relocation to permanent public housing (Housing Bureau, 2024).

Temporary demountable modular buildings have significant potential for relocation and reuse across multiple use cycles if Design for

Disassembly (DfD) principles are well implemented. Reusing these modular buildings can reduce the consumption of virgin materials, decrease demolition waste, and preserve environmental value (Yang et al., 2024). However, relocation and reuse activities may also lead to additional environmental impacts (Akbarnezhad et al., 2014). It has been suggested that modular units should be designed for assembly and disassembly at least five times over a period of 50 years to maximize their utility as temporary dwellings (Incelli et al., 2023). Nevertheless, there is limited evidence regarding the environmental viability of using demountable modular systems multiple times.

Given the potential environmental benefits and burdens associated with building reuse, a critical question arises: is the multi-cycle use of these demountable modular systems always environmentally viable? Specifically, the research question arises: how many years and how many times would these systems be reused to ensure minimal adverse environmental impacts? In other words, it is essential to determine the optimal number of use cycles of these systems and the duration of each cycle that would result in minimal environmental impacts. To address this research question, this study starts with a literature review by (1) understanding the environmental benefits and loads of building reuse

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and factors considered in the life cycle assessment (LCA) of building reuse and (2) identifying the environmental sustainability indicators used to determine the optimal multi-use scenarios. Based on the review, the research gaps, hypotheses, and objectives are formulated. Adaptive reuse is beyond the scope of the study; instead, a building reuse scenario refers to the process of partial or full disassembly and reassembly on a different site.

2. Literature review

2.1. Life cycle assessment of building reuse

The reuse of building components and recycling of building materials can offset carbon emissions associated with the production of raw materials, thereby generating notable environmental benefits (Bertin et al., 2022; Minunno et al., 2020). For example, Minunno et al. (2020) assessed the environmental benefits of reusing a modular building. They pointed out that the reuse of building components and recycling of the remaining building materials could lead to an approximately 88 % reduction in embodied carbon emissions. Similarly, Yang et al. (2024) evaluated the environmental impacts of reusing modular components in multiple use cycles. They found that reusing modular components and recycling building materials could generate lower embodied carbon emissions during the intermediate cycle(s). These findings confirm that significant environmental benefits can be obtained by implementing reuse and recycling strategies. Despite these environmental benefits, Akbarnezhad et al. (2014) indicated that the embodied energy and carbon might be associated with building reuse and recycling activities. Yang et al. (2024) also considered the embodied carbon emissions associated with various value retention processes, such as repair and replacement of certain building components.

As buildings are reused over long periods, operational carbon emissions tend to accumulate (Ibn-Mohammed et al., 2013). Generally, these emissions increase with the duration of a building's use because ongoing energy consumption contributes to them (Liang et al., 2022). As a consequence, the operational carbon emissions from a building may offset the environmental benefits of reusing it. Some studies have examined the trade-off between operational and embodied carbon emissions to help decide whether to demolish or reuse a building. For instance, Abbey et al. (2022) evaluated the operational and embodied carbon emissions of a commercial building to determine whether it should be reused, demolished, or retrofitted. In this regard, it is essential to consider both embodied and operational carbon emissions when evaluating the environmental impacts of building reuse.

Assessing the environmental impact of building reuse is complex because it is influenced by various factors. These factors may include recovery potential of building materials and components (i.e., reusability and recyclability) and value retention processes (i.e., repair, replacement, recycling, and transportation), which have been considered in the LCAs of building reuse (e.g., Antwi-Afari et al., 2023; Yang et al., 2024; Zheng et al., 2025; Lei et al., 2025). The recovery potential of building components and materials can be determined by their physical conditions and properties. For instance, material degradation, like concrete carbonation or steel corrosion, can directly lower the reuse rate of a building. Several studies have included material degradation in their environmental impact analyses of building reuse. For example, Lei et al. (2025) examined how material degradation affects reuse rates, suggesting that the extent of deterioration influences reuse. Similarly, Mollaei et al. (2023) estimated the recovery potential of building structures by considering building age, material properties, and component life expectancy. The process of building reuse often involves recycling unusable materials, which can bring both environmental benefits and burdens. In the study by Antwi-Afari et al. (2023), a sensitivity analysis was performed on a modular steel slab, and it was found that higher recyclability rates can reduce the environmental impacts associated with reuse and recycling strategies. Similarly, Bertin

et al. (2022) considered material recyclability while assessing the environmental impact of reusing and recycling concrete components. However, these studies often overlook the inherent uncertainties associated with recovery potential that can be influenced by weather and handling procedures. More specifically, these studies typically use deterministic values for reuse and recycling rates, which simplifies the analysis but fails to capture the dynamic and unpredictable nature of reuse practices (Igos et al., 2019). To address this gap, Yang et al. (2024) and Zheng et al. (2025) conducted uncertainty and global sensitivity analyses to generate probabilistic environmental outcomes by treating the reuse and repair rates of modular components as random variables.

Building reuse involves various value retention processes, which can result in additional environmental burdens. Value retention activities for buildings include, but are not limited to, component reclamation, repair, refurbishment, remanufacturing, recycling, and reverse logistics. Each of these activities involves different levels of resource consumption and generates carbon emissions (Nasr et al., 2018). Simpler activities like reuse and repair generally involve lower energy and resource demands, whereas processes such as replacement and refurbishment are typically more resource-intensive and may lead to higher environmental burdens (Russell and Nasr, 2019). Previous studies have preliminarily examined the environmental impacts associated with different value retention activities. For instance, Zheng et al. (2025) evaluated the environmental impacts of the reuse, repair, and replacement of modular components and found that the burdens from reuse and repair are significantly lower than those from replacement. In addition, the reuse of building components and materials often involves reverse logistics, and the associated environmental impacts should not be overlooked (Sobotka and Czaja, 2015). According to Chileshe et al. (2019), the building reuse processes involve the collection, sorting, reprocessing, and testing of building elements and materials, often occurring at different locations. Therefore, value retention activities are important in assessing the environmental impacts associated with building reuse.

Based on the above review, it is hypothesized that reusing a building over multiple cycles would be associated with increases in embodied and operational carbon emissions. Given the foreseeable increases in environmental impacts of building reuse, it may not always be environmentally viable to reuse a building system endlessly. Although previous studies have identified the environmental benefits and burdens associated with building reuse, there has been limited exploration of the environmental impacts of various multi-use cycle scenarios concerning the number of cycles and the duration of each cycle. In other words, there is a notable gap in research that explores how many years and how many times building systems can be reused while remaining minimal adverse environmental impacts.

2.2. Indicators of environmental sustainability

Embodied carbon has become a critical indicator for evaluating the buildings' environmental impacts (Kang et al., 2015). Specifically, activities such as production, transportation, assembly, disassembly, and relocation can significantly contribute to embodied carbon emissions. Minimizing embodied carbon throughout a building's lifecycle is essential for achieving net-zero goals (Drewniok et al., 2023). In this regard, a life cycle embodied carbon analysis can offer valuable insights for decision-makers evaluating the environmental impacts of the building system across multiple life cycles. For instance, Yang et al. (2024) assessed the embodied carbon emissions of producing and reusing a modular unit and indicated that reuse could result in negative environmental impacts. Similarly, Wen et al. (2024) revealed that reusing steel modular components resulted in negative embodied carbon emissions at the end-of-life stage.

In addition to embodied carbon, operational carbon emissions generated from energy consumption during the use phase are also important for understanding the environmental impacts of building reuse (Akande et al., 2016). Operational carbon can account for 60 %–

80 % of a building's lifecycle carbon emissions (Wang et al., 2022). Given its dominant role, it is essential to consider operational carbon when evaluating building reuse strategies. Previous research has incorporated operational carbon emissions into the decision-making process for building reuse. For example, Abbey et al. (2022) evaluated both operational and embodied carbon emissions to determine the most appropriate end-of-life planning strategy, including demolition, direct reuse, or retrofit. They found that the retrofitting option resulted in lower carbon emissions compared to direct reuse. Overall, carbon emissions serve as a key indicator of environmental sustainability. A comprehensive understanding of both embodied and operational carbon emissions is essential for informed decision-making and promoting sustainable building practices.

The environmental cost of carbon emissions refers to the damage value linked to climate change caused by the release of an additional ton of carbon dioxide equivalent into the atmosphere (Lu and Deng, 2023; Tol, 2005). By monetizing carbon emissions and considering the discount rate, future climate-induced costs can be estimated (Nydahl et al., 2019, 2022). This feature of environmental cost is crucial as it provides valuable insights into the potential impact of climate damage (Nydahl et al., 2022) due to future relocation and reuse activities. For example, the building reuse process entails various activities that contribute to carbon emissions and associated environmental costs. The time value of environmental impacts should be considered for multi-use cycles of building components as the cost to compensate for environmental damage increases with time (Wang et al., 2018). Monetizing environmental impacts allows for the estimation of climate-induced costs in a manner that is accessible to the general public (Arrigoni et al., 2023). Many studies have evaluated the cost of carbon emissions with building assets, as it represents a significant portion of overall environmental costs (Lu and Deng, 2023). For example, Nydahl et al. (2022) evaluated the environmental cost of carbon emissions throughout a building's lifecycle by multiplying emissions by a monetary factor. They suggested that the cost of carbon emissions could function as a tax to influence economic decision-making and promote climate change mitigation in the construction sector. Similarly, Luo et al. (2021), Chou and Yeh (2015), and Jayasena et al. (2022) utilized carbon tax rates to monetize the carbon emissions of building assets.

While evaluating carbon emissions and the associated environmental cost can help identify the environmental impact of building reuse, it remains uncertain how much value can be preserved after multiple use cycles, referred to as residual value in this study. For instance, if modular components are demolished before the end of their intended lifespan, it can result in a loss of value, as their environmental impact remains unamortized. Research on residual value is still in its early stages (Jiang et al., 2022). Obrecht et al. (2021) defined residual value as the sum of unamortized environmental emissions relative to the designed service life. A high residual value for building components or materials indicates that their environmental impacts are not fully utilized by the end of their service lives, resulting in greater value loss. Assessing life cycle carbon emissions along with the corresponding residual value can provide deeper insights into the extent of impact generated, amortized, and ultimately lost (Jiang et al., 2022; Obrecht et al., 2021).

To ascertain the environmental impacts of a (demountable) building system over multiple use cycles, the environmental cost of carbon emissions and residual value are viewed as two indicators of environmental sustainability in this study. On the one hand, the environmental cost represents the monetary value of environmental impacts (embodied and operational carbon emissions in this research), reflecting the present value of future climate change impacts associated with each ton of carbon dioxide emitted (Saleh et al., 2019). Estimating environmental costs can offer deeper insights than simply conducting a LCA of embodied and operational carbon emissions, as it quantifies the present value of future costs arising from value retention and operational activities, facilitating timely decision-making in carbon reduction strategies (Luo et al., 2021). On the other hand, the residual value indicates

the amount of carbon emissions that remain unamortized. Assessing residual value provides insights into the carbon emissions generated, amortized, and ultimately lost. As a result, the analysis of residual value is more suitable than a LCA because it not only evaluates the total carbon emissions produced during the multi-use cycle process but also reflects the remaining carbon emissions that have yet to be amortized after multiple uses. Thus, a residual value offers a more comprehensive view of the environmental impacts of building reuse across multiple cycles.

2.3. Research gaps and aim

Several research gaps in assessing the environmental impact of building reuse over multiple cycles have been identified. First, although past research has made attempts to evaluate the environmental impacts of reusing building components (Brütting et al., 2020), it raises a question of whether considering minimal environmental impacts alone is sufficient for determining optimal multi-use cycle scenarios for building components, especially given that time discounting remains a contentious issue in environmental impact analysis (Wang et al., 2018). Accordingly, the assessment of the environmental cost and residual value could provide new insights into the environmental impacts of building reuse over multiple cycles, taking time into account. Secondly, uncertainties associated with building reuse (Hossain et al., 2020) may affect the predictability of the environmental impacts associated with reuse activities in the future. These uncertainties can lead to variations in the environmental impacts of building reuse, thereby complicating decision-making regarding optimal multi-use cycle scenarios. This challenge, however, can be addressed through the application of uncertain analysis, which has been used in many LCA studies that incorporate uncertain inputs associated with building reuse and recycling (e.g., Yang et al., 2024). Finally, although previous studies have recognized that various factors and activities have different environmental impacts, few have examined how these factors are dynamic and can change over time, such as the impact of material degradation on reuse rates and how repair rates may fluctuate throughout a building's life cycle. These temporal factors also influence the long-term environmental impact of reusing demountable modular building systems. Therefore, this work incorporates this time-dependent variable into the life cycle analysis, enabling practitioners to enhance the LCA methodologies for building reuse over multiple cycles (van Stijn et al., 2021).

Considering the important role of environmental cost and residual value in determining the environmental impacts of building reuse, the research question mentioned in Section 1 can be further specified as how many use cycles and their durations would result in minimal environmental costs and residual value. Accordingly, this study aims to identify the optimal multi-use cycle scenarios for reusing a demountable modular building system that minimizes both the environmental costs and residual value, using a demountable modular unit located in Hong Kong as a case study. Each scenario corresponds to a specific number of use cycles and the duration of each cycle. The research methods employed include a LCA of embodied and operational carbon emissions, residual value analysis, and monetization assessment, followed by multi-objective optimization under uncertainty, and sensitivity and scenario analyses. This study significantly contributes to the existing literature on the environmental cost of embodied and operational carbon emissions and the residual value of building reuse, an area that has received limited attention. The optimal multi-use cycle scenarios identified can aid owners in making decisions on sustainable end-of-life planning of temporary modular buildings. The uncertainty analysis adopts a stochastic approach, effectively addressing the limitations of deterministic methods by accounting for uncertainties (e.g., material degradation) in input variables (Baldoni et al., 2019; Huang et al., 2021), especially when future reuse cycles are highly uncertain (Yang et al., 2024). Decisions based solely on deterministic value often prove unrealistic in practical situations (Pandey and van der Weide, 2017). Thus, a stochastic perspective can enhance informed decision-making under

uncertain future reuse scenarios. Additionally, the sensitivity and scenario analyses can identify the most influential parameters that lead to significant changes in the LCA outcomes. Overall, the findings of this research can benefit construction practitioners by deepening their understanding of the environmental impacts of building assets across multiple use cycles and facilitating sustainable end-of-life planning within a circular economy.

3. Methods and materials

3.1. Research problem definition

The above literature review reveals that there is a limited attempt to identify the optimal reuse scenarios of demountable buildings when considering their environmental impacts. The determination of optimal reuse scenarios enables policymakers and practitioners to implement suitable strategies for planning and coordinating the future use cycles of demountable buildings that minimize environmental impacts associated with repeated reuses. To achieve this goal, a research question is formulated: What are the optimal reuse scenarios of demountable buildings that minimize both environmental cost and residual value? Based on this question, the research hypotheses are given as follows:

H1. The increase in the number of cycles (n) is associated with an increase in environmental cost. This is because more reuse cycles are involved, more value retention and operational activities result in more embodied and operational carbon emissions.

H2. A longer total service life ($\sum_i^n l_i$) is associated with a higher environmental cost and a lower residual value. This is because the longer service life, the more operational carbon emissions are generated, but the lower residual value after amortization over a longer period of time.

H3. Based on **H1** and **H2**, it is further inferred that to achieve lower environmental cost and residual value, the number of cycles should be smaller and the total service life should be longer. Therefore, it is considered that there exist optimal reuse scenarios (n, l) where specific combinations of use cycles (n) and corresponding length of cycle (l), representing the minimal environmental cost and residual value.

The research framework (Fig. 1) was proposed to test these hypotheses as follows. Firstly, a deterministic life cycle impact model was developed to quantify the embodied and operational carbon emissions of a demountable modular building system across multiple life cycles, thereby determining the corresponding residual value and environmental cost. Secondly, a probabilistic life cycle impact model was established by employing probability density functions (PDFs) for uncertain parameters that generate random values accordingly. Thirdly, multi-objective robust optimization was performed by incorporating those uncertain inputs to identify optimal multi-use cycle(s) that achieve the lowest environmental costs and residual value. Finally, global sensitivity and scenario analyses were carried out to examine how

variations in parameters affect the environmental cost and residual value of the optimal scenarios.

3.2. Case study

The case study focuses on a temporary demountable modular building in Hong Kong. In 2022, this building was required to be dismantled due to the expiration of its land tenancy agreement. According to the planning scheme, it would be repaired, relocated, and reassembled at a new project site to serve a larger low-income population. The relocation project received approval from the regulatory authority, which appointed a task force for transitional housing to act as the technical coordinator for the execution of the relocation works (Luk et al., 2023).

The investigated demountable modular building system is composed of modular units with identical specifications. These modular units were initially manufactured from new modular components at the fabrication factory. Following fabrication, the modular units were transported from the prefabrication facility to the project site, where they were sequentially assembled into the final structure. After construction, the modular building entered its use phase. When its initial use cycle ends, the modular units were disassembled and transported to warehouses for repair and maintenance. Once repaired, the modular units were moved to a new project site for reassembly and recommissioning.

As illustrated in Fig. 2, the typical modular unit consists of steel frames, bolt-nut connectors, concrete slabs, and partition walls. The adjacent modular units are fixed through bolt-nut connectors. The inherent modular design facilitates easy disassembly, relocation, and reuse of the unit. The modular unit is 2.9 m in height, 2.4 m in width, and 12.2 m in length. It was made entirely of new materials without recycled materials or components. It is assumed that the modular unit would be destroyed for recycling and/or disposal after its service life. Temporary modular building systems typically have a lifespan ranging from 5 to 10 years (UNECE, 2021). However, it has been reported that the expected service life of temporary buildings can extend up to 20 years (Grosso and Thiebat, 2015). Given the nature of temporary buildings, this study assumes that the length of each use cycle could be 5, 10, 15, 20, or 25 years. While the designed service lifetime of the modular unit is 50 years, the corresponding number of use cycles can vary from 2 to 10, resulting in a total of 938 multi-use cycle scenarios.

3.3. Goal and scope definition

A multi-cycle environmental impact assessment was performed to determine the embodied and operational carbon emissions of the demountable modular unit, followed by identifying the corresponding environmental cost and residual value produced during multiple-use cycles. A single-use cycle of the modular unit is defined as the time period commencing with the production or assembly of the modular unit and ending with its disassembly or disposal. The fundamental characteristics of the modular unit remain consistent in each use cycle, with its

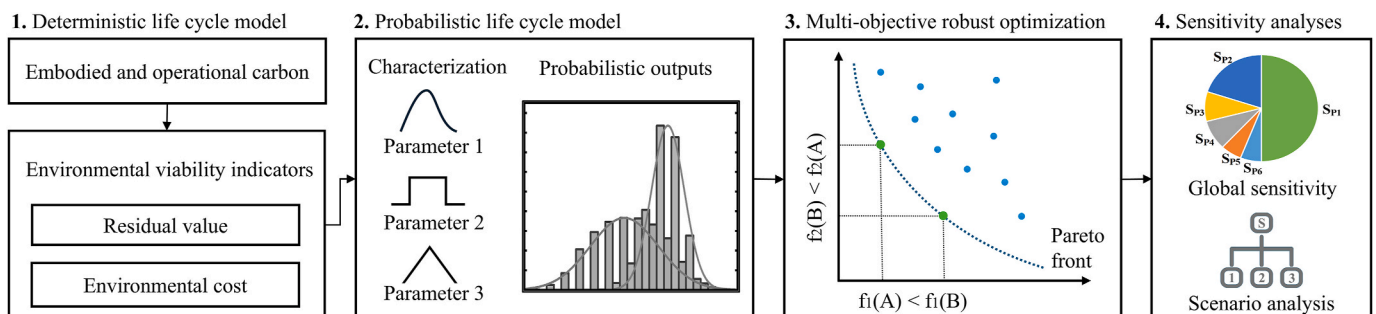


Fig. 1. Research framework.

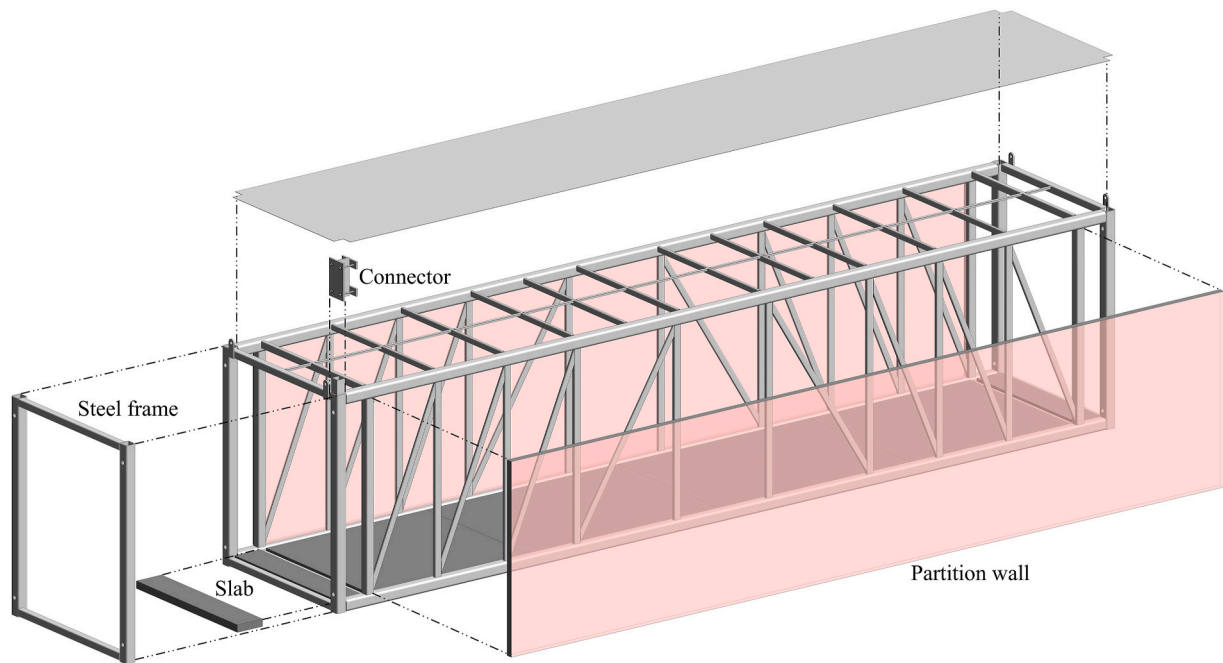


Fig. 2. The modular unit analyzed in this study.

materials and components considered for either direct reuse or reuse after value retention activities (e.g., repair and replacement) within the same system. This assessment considers the different value retention activities for the core modular components (i.e., the steel frames and concrete slabs) and subcomponents (i.e., partition walls and bolt-nut connectors) (Yang et al., 2024). The functional unit utilized in the assessment is the modular unit itself, with a maximum service period of 50 years. It is noteworthy that the demountable modular system is regarded as non-reusable beyond its lifespan, during which the multi-reuse takes place. The assessment investigates the embodied and operational carbon emissions produced by the reuse of the modular unit across multi-use cycles. The life cycle stages examined include the raw materials production and assembly processes (LCA-module A), operational consumption (LCA-module B), disassembly and disposal processes (LCA-module C), and the impacts related to reuse and recycling processes (LCA-module D). Module D considers the environmental impact of value retention activities such as replacement, repair, and recycling. However, the recyclable materials are excluded from the current system boundary because they are assumed not to be reintroduced into the same building system.

3.4. Life cycle inventory

The life cycle inventory (LCI) analysis involves breaking down the processes associated with multiple use cycles into sub-processes. Each sub-process of a use cycle includes activities such as production, transport, assembly, disassembly, value retention activities, relocation, reassembly, and disposal, if applicable. To obtain LCI data for each sub-process, 2D design drawings of the modular unit were employed to determine the material quantities required for the steel frame, slabs, partition walls, and bolt-nut connectors. Moreover, site engineers who participated in the assembly and disassembly activities were requested to determine the number of cranes and machines utilized and their respective operating hours (Construction Industry Council, 2022). In addition, operational water and electricity consumption were estimated based on average per capita annual usage in Hong Kong (Electrical and Mechanical Services Department, 2024; Water Supplies Department, 2015). Finally, the PDFs of uncertain parameters were constructed based on project records, government documents, online data sources, and

relevant literature.

The ReCiPe mid-point method impact category 'climate change' was utilized to determine embodied and operational carbon emissions of the modular unit. Emission coefficients corresponding to specific processes and activities were gathered from the Ecoinvent 3.10 cut-off database. The ReCiPe mid-point level monetization factors used in this study are compatible with the selected LCA impact categories. At the mid-point level, uncertainty is relatively low and acceptance is high (Landgraf et al., 2022). In contrast, endpoint indicators, such as damage to human health, ecosystem diversity, and resource availability, further aggregate and convert mid-point indicators, often based on proprietary models, which leads to relatively high uncertainty and lower acceptance (Goedkoop, 2008; Landgraf et al., 2022).

The environmental pricing methodology developed by CE Delft in Environmental Price Handbook EU28 is based on the ReCiPe 2016 Midpoint(H) methodology (De Bruyn et al., 2018), thus aligning with the aforementioned life cycle impact analysis. The prices referenced here represent damage costs, indicating the willingness of citizens to pay to avoid exposure to an additional 1 kg of environmental pollution, expressed in EUR per kg of emissions (R. Zhang et al., 2024). This pricing scheme is considered a preferred tool for calculating externalities compared to other options (e.g., Stepwise, Ecotax) because it adheres to the impact categorization defined in ReCiPe (2016) (Phuang et al., 2023). It has also been applied in non-European countries, such as Malaysia (Phuang et al., 2023) and China (Guo et al., 2023), when the localized monetization factors are lacking. To address the challenge of lacking a local environmental price database, it is recommended to adopt higher environmental prices for carbon emissions (i.e., $\text{€}_{2015} = 0.094$ per kg CO₂-eq) until a global set of country-specific prices becomes available (Zhang et al., 2024). This environmental price is then adjusted to Hong Kong dollars using the consumer price index and exchange rate, resulting in $\text{HK}_{2019} = 0.864$ per kg CO₂-eq. The reference year was set to 2019 because construction of the case building commenced that year. Although the Environmental Price Handbook EU27 (De Vries et al., 2024) has been released recently, this study adopted the old version (De Bruyn et al., 2018) because the case building was built in 2019. The present value of the environmental cost was subsequently discounted, with a reference discount rate of 3% assumed for the environmental cost (Luo et al., 2021), which aligns with

suggested social discount rates for monetizing environmental impacts (Lu and Deng, 2023; Nydahl et al., 2019).

3.5. Deterministic life cycle impact model

The deterministic life cycle impact model was developed for the case study. This model considered all the life cycle stages involved in modular unit across multiple use cycles to assess the embodied and operational carbon emissions. Moreover, we further calculated the residual value, which represents the unamortized carbon emissions when reaching a building's end-of-life. A lower residual value indicates that the building tended to be fully utilized, while a higher residual value suggests that the remaining impact could not be fully amortized, resulting in a loss of value. This study focuses solely on environmental cost, while other costs, such as life cycle costing (e.g., production and construction costs) are excluded from the analysis. At the end of the final use cycle, the avoided burden (0:100) approach was utilized for impact allocation. The life cycle embodied and operational carbon emissions, residual value, and environmental cost are represented by Eq. (1), Eq. (2), and Eq. (3), respectively. The residual value was calculated at the end-of-life stage when direct reuse is no longer feasible (Eq. (2)). Additional details regarding the analyses of embodied and operational carbon emissions, environmental cost, and residual value can be found in Supplementary Material A.

$$\sum_i^N \sum_c^C \sum_m^M E = \sum_c^C \sum_m^M P_{1,c,m} + \sum_i^N (A_i + D_i) + \sum_2^{N-1} \sum_c^C \sum_m^M VRP_{i,c,m} + \sum_c^C \times \sum_m^M Eol_{n,c,m} + \sum_t^{\bar{l}_i} (O_w + O_{ele}) \quad \text{Eq. (1)}$$

$$RV = \left(1 - \frac{\bar{l}_i}{SL}\right) \cdot \sum_i^N \sum_c^C \sum_m^M E \quad \text{Eq. (2)}$$

$$\sum_i^N \sum_c^C \sum_m^M C_E = \sum_c^C \sum_m^M PC_{1,c,m} + \sum_i^N (AC_i + DC_i) + \sum_2^{N-1} \sum_c^C \sum_m^M VRC_{i,c,m} + \sum_c^C \sum_m^M EC_{n,c,m} + \sum_t^{\bar{l}_i} (OC_w + OC_{ele}) \quad \text{Eq. (3)}$$

Where: E , RV , and C_E are the environmental impact (embodied and operational carbon emissions), residual value, and environmental cost, respectively, N is the total number of cycles, i is the i th use cycle, C is the set of components, c is the c th type of component, M is the set of materials, m is the m th type of material, \bar{l}_i is the cumulative use period of i nos. of use cycles, t is the t th year of use (start from 1), $P_{1,c,m}$ is the embodied carbon emissions of the primary production of the module consisting of component c and material m , A_i , D_i , and $VRP_{i,c,m}$ is the embodied carbon emissions of assembly, disassembly, and value retention process, respectively, $Eol_{n,c,m}$ is the embodied carbon emissions at the end of the last use cycle, O_w is the operational carbon emission of the annual water consumption, O_{ele} is the operational carbon emission of the annual electricity consumption; SL is the service lifetime (i.e., 50 years); $PC_{1,c,m}$ is the environmental cost (embodied and operational carbon emissions) of the primary production of the module consisting of component c and material m , $AC_i + DC_i$ is the present value of the environmental cost of i nos. of disassembly and assembly of the module, $VRC_{i,c,m}$ is the present value of the environmental cost of value retention activities for component c and material m in the i th use cycle, $EC_{n,c,m}$ is the environmental cost of end-of-life treatments of the module consisting of component c and material m , OC_w is the present value of the environmental cost of the annual operational water consumption, OC_{ele} is the present value of the environmental cost of the annual operational

electricity consumption.

To account for the influence of material degradation on the reusability of building components, this study considers that the repair and replacement rates of components change over time, as shown in Eq. (4) and Eq. (5). Eq. (4) is a function of the repair rate ($ra_{i,c}$) that reflects the degradation of components over time, thereby affecting their repairability. The repair rate is estimated based on a building's age, a component's life expectancy, and an adjustment factor (f_c). The adjustment factor accounts for the technical challenges associated with repairing a component, which may be influenced by the structure's geometry, design specifications, and the types of connections used in a building (Mollaei et al., 2023). Similarly, for the replacement rate ($rb_{i,c}$), an adjustment factor (g_c) is also introduced to reflect challenges and constraints associated with replacing a component. This factor, together with the effects of time, captures how the replacement rate varies with a building's age, a component's life expectancy, and technical challenges.

$$ra_{i,c} = f_c \times \left(e^{i-\alpha_c} + \frac{l_i}{10 \cdot \alpha_c} \right) \quad \text{Eq. (4)}$$

$$rb_{i,c} = g_c \times \frac{SL}{\alpha_c} \quad \text{Eq. (5)}$$

Where: $ra_{i,c}$ is the repair rate of component c in the i th use cycle, $rb_{i,c}$ is the replacement rate of component c in the i th use cycle; f_c and g_c are the adjustment factors considered the technical challenges associated with repairing and replacing a component, respectively, which may depend on the structure's geometry, design specifications, and the connections utilized in the building; l_i is the use period of the building (years), α_c is the life expectancy of a component c (years), and SL is the service life of the building (50 years).

3.6. Probabilistic life cycle impact model

The probabilistic life cycle impact model was developed based on the deterministic model. This model incorporates PDFs of uncertain parameters and generates random values from the specified PDFs to produce probabilistic outputs. Based on the literature review and case study, three types of uncertain parameters are considered. Firstly, factors influencing material recovery efficiency, including the repair and replacement rates, were evaluated (Luk et al., 2023). For instance, core components may require repairs, such as recoating, rectification, and polishing, to sustain the integrity of the building system over time. Additionally, non-reusable components, like bolt-nut joints, may be replaced due to the advantages of the demountable modular system. This replacement process necessitates the use of new components to replace outdated ones and involves the recycling and/or disposal of the removed components. When the modular unit and its components are considered inappropriate for reuse, they are deemed as standard construction demolition waste and processed for sorting, recycling, and/or landfill. Secondly, to address uncertainties regarding the recyclability rate of materials in the future use cycle(s), a uniform distribution was assumed for each uncertain input parameter to reflect the variability (Pannier et al., 2018; Yang et al., 2024). Finally, transport distances were also regarded as uncertain variables, for which a normal distribution was applied (Pannier et al., 2018). The PDFs of uncertain parameters are provided in Supplementary Material A.

Notably, the research team conducted comprehensive tracking throughout the entire process of modular unit disassembly, relocation, repair, and reassembly at the first use cycle. In collaboration with the project team, seven rounds of on-site inspections were performed to assess the condition of modular units before and after disassembly, as well as during storage periods. No component degradation related to handling or transportation processes was observed (Luk et al., 2023). During the storage period, all modular units were protected with specially waterproof covers, which effectively prevented deterioration

caused by extreme weather conditions during storage (Luk et al., 2023). Consequently, degradation caused by weather was not incorporated into the modelling framework.

3.7. Multi-objective robust optimization under uncertainties

Multiple-objective optimization was performed to determine the optimal number of use cycles and the length of each cycle, aiming to minimize environmental cost and residual value across multiple use cycles. The mathematical model was developed based on the impact analysis formulations (Eqs. (2) and (3)). The multi-objective optimization applies a trade-off rationale to address two conflicting objectives: minimizing residual value and environmental cost over the multiple uses of the modular unit.

To tackle the inherent uncertainty in the input parameters, a multi-objective robust optimization approach was used to determine the 90th percentile of environmental cost and residual value under uncertainties (Galimshina et al., 2021). The Pareto front results represent the robust optimal solutions for the 90th percentile of probabilistic environmental cost and residual value, implying that these optimal solutions are obtained when input variables fluctuate (Galimshina et al., 2021). This ensures that the model fully considers the influence of uncertainties and produces optimal solutions that are more resilient and adaptable. For each combination of use cycles, the uncertain parameters were propagated through the computational model described in Section 3.6, and a Monte Carlo simulation was employed to evaluate the corresponding quantiles of environmental cost and residual value, iterating through all the combinations to identify non-dominated optimal solutions. These solutions collectively form a Pareto front, which represents a trade-off curve where improvement in one objective results in a compromise in the other objective. The Pareto front provides decision-makers with a set of optimal solutions, offering the flexibility to select the most appropriate option based on project-specific priorities. By leveraging this approach, decision-makers gain a comprehensive understanding of potential trade-offs, enabling informed decisions that balance environmental cost with residual value, ultimately achieving environmental sustainability for reusing modular building systems. The multi-objective robust optimization model was coded in C# to ensure computational efficiency and enable the exploration of complex scenarios and large datasets.

3.8. Sensitivity and scenario analyses

To identify the variables, including recycling/reuse rates, repair/replacement rates, and transport distances, that most significantly contribute to the LCA results of Pareto-optimal scenarios, a global sensitivity analysis was conducted using Sobol's indices (Sobol', 2001). Both first-order and total-order sensitivity indices were considered. On the one hand, the first-order indices reflect how much each input variable affects the output variance when all other variables are held constant. On the other hand, the total order indices evaluates each input variable's impact on the output variance while accounting for any interactions with other variables. The global sensitivity analysis was conducted in PyCharm IDE using the SALib package.

The above analysis was performed under a baseline scenario, where emission factors were retrieved from the Ecoinvent V3.10 database, consumption of electricity and water remained constant over the years, and the environmental price was converted from the Environmental Price Handbook in 2018 as explained in Section 3.4. To test the variations of these factors on the environmental cost and residual value, six scenario analyses were performed: (1) electricity and water consumption increasing by 0.35 % and 0.5 % per annum, respectively, (2) electricity and water consumption increasing by 0.7 % and 1 % per annum, respectively, (3) emission factors retrieved from ELCD database, (4) emission factors retrieved from GaBi database, (5) environmental price obtained from Landgraf et al. (2022), and (6) environmental price

obtained from Eldh and Johansson (2006). The scenario analyses were carried out in Visual Studio 2022.

4. Results

4.1. Optimal number of cycles and length of cycles

As illustrated in Fig. 3, the environmental cost of embodied and operational carbon emissions tends to rise with an increasing length of the cycles when the number of cycles remains constant. Such an increase may be mainly attributed to the increasing operational carbon emissions associated with longer operational periods. The environmental cost of carbon emissions slightly increases with an increasing number of cycles when the length of total service life remains constant. Such an increase is mainly attributed to the increasing embodied carbon emissions associated with more frequent material replacement and repair activities that occur with each additional cycle. To minimize the environmental cost, it is suggested to limit the number of cycles and the length of total service life, as fewer cycles correspond to less embodied carbon emissions and shorter length contributes to lower operational carbon emissions.

Residual value reaches its minimum (i.e., zero) when the cycle length equals the designed service life (i.e., 50 years), indicating that the embodied and operational carbon emissions of the modular unit have been entirely amortized. This indicates that a longer cycle length allows for more embodied and operational carbon emissions to be amortized. Conversely, a shorter cycle length implies that embodied and operational carbon emissions cannot be fully amortized, resulting in a loss of value. To minimize residual value, the length of the cycles should be extended. However, when the number of cycles remains constant, the residual value represents a parabolic relationship with the length of the cycles (Fig. 4). Special attention should be paid to the scenarios when the total service life ranges from 10 to 25 years, where the residual value for 10 years of service life is lower than that for 15, 20, and 25 years. It is inferred that when the total service life increases from 10 to 25, corresponding carbon emissions would have a remarkable increase (observed from Fig. 3), but the total service life is not long enough to amortize those impacts. The length of cycles with a total of 10 years is associated with a smaller environmental impact to be amortized and thus the corresponding residual value is smaller. These results further imply that a "junior age" of the modular unit (i.e., between 10 and 25 years old) would result in a higher residual value. In contrast, either the shortest service life (i.e., 10 years) or longer than half of the total life span may

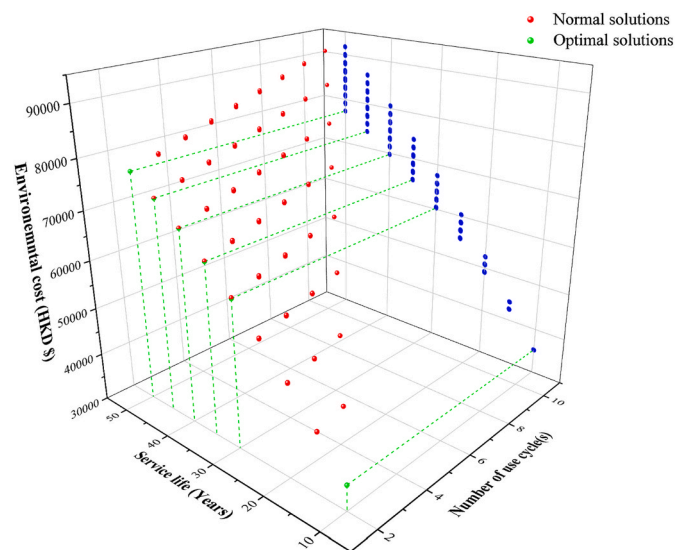


Fig. 3. The environmental cost associated with the number of use cycles and total service life.

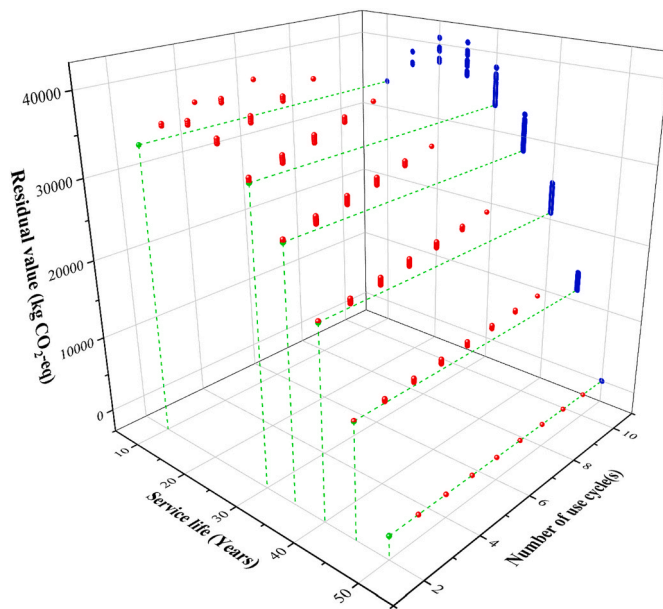


Fig. 4. The residual value associated with the number of use cycles and total service life.

result in relatively lower residual value and thus less loss of value.

Minimizing the environmental cost alone (Fig. 3) may compromise residual value when the number of cycles is low but the cycle lengths are relatively short (Fig. 4). This scenario can hinder the full amortization of embodied and operational carbon emissions, leading to a loss of value. In other words, if the modular unit reaches the end of its life after only a short period of use, the resources and time invested in production, assembly, operation, and disassembly would be largely viewed as waste. Conversely, focusing solely on minimizing residual value could result in a higher environmental cost when the number of cycles increases (Fig. 3). While carbon emissions can be largely amortized in this case, the overall environmental cost may rise due to additional emissions generated from value retention and operational activities alongside the increased number of cycles (Fig. 3). Therefore, it is essential to consider a trade-off between the number of cycles and their lengths to minimize both environmental cost and residual value.

The six Pareto-optimal solutions were identified: [5-yr, 5-yr], [5-yr, 25-yr], [10-yr, 25-yr], [15-yr, 25-yr], [20-yr, 25-yr], and [25-yr, 25-yr]. In the present case study of a temporary demountable modular building system in Hong Kong, it was found that the Pareto-optimal number of cycles is two. This suggests that reusing the modular unit more than twice could be relatively less environmentally viable due to the increased environmental cost of embodied and operational carbon emissions. While the number of cycles remains two, the environmental cost increases as the length of total service life extends, whilst residual value increases to the highest at 25 years and then decreases. The Pareto-optimal solutions indicate that the length of the first use cycle should not be longer than the second one. This is because a longer use cycle in the first cycle may require more intensive repair and replacement activities, given that the time-dependent degradation rates of steel, concrete, and gypsum board have been assumed (Supplementary Material A). The results also indicate that if the length of the first use cycle is 5 years or longer, the length of the second use cycle generally should be 25 years. This is likely because these scenarios attempt to amortize the embodied and operational carbon emissions with the greatest effort (i.e., the maximal service life in each cycle), which would result in lower residual value compared to others. Furthermore, a special Pareto-optimal solution [5-yr, 5-yr] revealed that a relatively shorter service life would also be environmentally viable because such a shorter service life was associated with less environmental impacts and environmental

cost during construction and operation phases, even though its residual value was higher than the other Pareto-optimal solutions.

4.2. Probabilistic outcomes of environmental cost and residual value

Fig. 5 presents the probabilistic results of the six Pareto-optimal solutions. It shows that environmental cost increases while residual value decreases with longer service life. The residual value reaches zero when the first and second cycles are each set to 25 years, which accounts for half of the total designed lifespan. The [5-yr, 5-yr] scenario yields the highest residual value and the lowest environmental cost among all optimal solutions. This outcome occurs because the shortest service life with only 10 years, indicates that most of the environmental impact from producing, assembling, operating, and disassembling the modular unit has not yet been amortized. There is a remarkable decrease in residual value when the total service life is more than 35 years, implying that the embodied and operational impacts can be significantly amortized when the total service life is longer enough.

Additionally, the environmental cost of the [25-yr, 25-yr] scenario almost doubles that of the [5-yr, 5-yr] scenario. It further suggests that the environmental cost of operational carbon emissions tends to increase remarkably with a longer total service life. Although the first cycle of the [25-yr, 25-yr] scenario is longer than that of [5-yr, 5-yr], leading to potentially greater material degradation, the associated replacement and repair activities result in only slightly higher embodied carbon emissions. Operational carbon emissions would be the primary contributor to the environmental cost in the [25-yr, 25-yr] scenario.

4.3. Results of global sensitivity analysis

The results of the global sensitivity analysis indicate that there are no significant differences in the influential factors across all Pareto-optimal scenarios. Fig. 6 illustrates the results of the global sensitivity analysis for a Pareto-optimal scenario [15-yr, 25-yr]. The primary factor influencing the variation in environmental cost and residual value is the change in the recycling rate of the steel frame. This suggests that increasing the recycling rate of steel at the end of the second use cycle would substantially offset the embodied carbon emissions, increasing the environmental benefits. Similarly, the recycling of replaced steel and partition walls may also contribute to these benefits. Consequently, both residual value and environmental cost would decrease due to the offset in embodied carbon emissions from recycling. The repair rate of the steel frame and concrete slab can significantly impact the variation in environmental cost and residual value, while the replacement rate of steel connectors and partition walls emerges as a key influential factor. The value retention activities associated with repair and replacement consume raw materials, thereby contributing to increased embodied carbon emissions. As a result, both residual value and environmental cost are likely to rise alongside the growing embodied carbon emissions due to these value retention activities.

Additionally, variations in the transport distance of steel and concrete materials from the manufacturing facility to the prefabrication factory can significantly affect environmental cost and residual value. Changes in the transport distance of concrete slabs from the prefabrication factory to the construction site also significantly influence the variation of the environmental cost and residual value. These findings suggest that utilizing local materials and local prefabrication factories is recommended for minimizing the environmental cost and residual value for multi-use cycles of building systems. However, the transport distance from the material manufacturing factory to the prefabrication factory primarily affects the environmental impacts during the production stage of the first life cycle (assuming that no production of new modules in the subsequent cycles). Variations in transport distance among the site, sorting facilities, warehouses, and recycling facilities do not significantly influence the change in environmental cost and residual value. Therefore, logistics between subsequent cycles may have a negligible

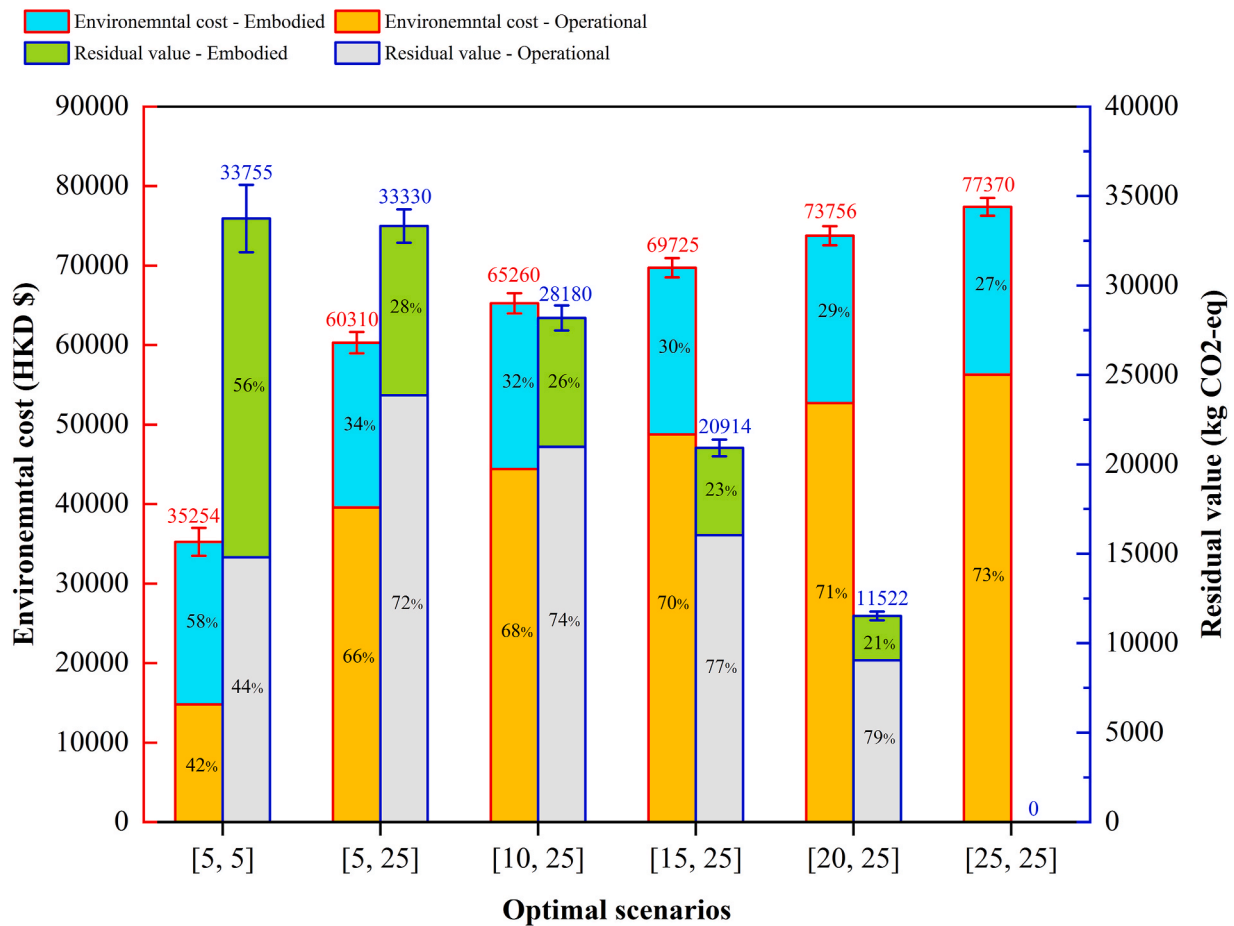


Fig. 5. Probabilistic outcomes of environmental cost and residual value of the six Pareto-optimal scenarios.

effect on the environmental impacts during subsequent use cycles.

4.4. Results of scenario analysis

The above global sensitivity analyses were performed under a baseline scenario where emission factors were retrieved from the Ecoinvent v3.10 database, the consumption of electricity and water was assumed to remain constant over the years, and the environmental price was converted from the Environmental Price Handbook in 2018, as explained in Section 3.8. The variations of these factors on the environmental cost and residual value of Pareto-optimal scenarios were tested, using [15-yr, 25-yr] as an example. As illustrated in Table 1, the results of scenario analysis reveal that the increases in electricity and water consumption during the operation stage result in increases in environmental cost and residual value. The decreases in environmental price obviously lead to the reduction of environmental cost. The use of different sources of background data considerably influences environmental cost and residual value.

5. Discussion

5.1. End-of-life decision making for multiple uses of demountable modular components

While significant efforts have been made to identify the environmental benefits of reusing building components (De Wolf et al., 2020; Eberhardt et al., 2019; van Stijn et al., 2021, 2022), there has been limited focus on determining the extent to which the number of cycles and their durations can be environmentally sustainable for reusing modular components from a multi-cycling perspective. This paper

addresses this knowledge gap by identifying the optimal combinations of the cycles' number and each cycle length that minimize both the environmental cost of carbon emissions and residual value. To the authors' best knowledge, this paper represents one of the first studies to determine the optimal scenarios for the multiple uses of demountable modular components. The identified optimal combinations of cycle number and cycle length can help provide practical insights for decision-makers planning the sustainable reuse of demountable modular building systems.

This study identifies six Pareto-optimal scenarios for the repeated reuse of modular components, successfully achieving the dual objectives of minimizing the environmental cost of embodied and operational carbon emissions and minimizing residual value. These optimal scenarios confirm the environmental viability of reusing modular components multiple times compared to other scenarios. Specifically, the optimal number of cycles is two, indicating that exceeding this range may lead to higher environmental costs, thereby undermining environmental viability. Notably, in the Pareto-optimal scenario [5-yr, 5-yr], the modular unit is utilized for a total of only 10 years, implying that most of the carbon emissions over the two use cycles remain unamortized. This scenario has the highest residual value among all the optimal scenarios while achieving the lowest environmental cost due to its relatively short service lifetime. Conversely, the Pareto-optimal scenario [25-yr, 25-yr] results in zero residual value when the modular component has been fully utilized within its designed lifespan, but it incurs the highest environmental cost among all optimal scenarios due to its longest service lifetime. This finding aligns with the notion that the social cost of greenhouse gases increases over time, as future emissions are expected to cause greater incremental damages due to the escalating pressures on physical and economic systems from climate change (US



Fig. 6. Global sensitivity analysis of [15-yr, 25-yr] scenario. RV represents residual value, C_E represents environmental cost. r_{rec} represents recycling rate, r_a represents repair rate, r_b represents replacement rate, $d_{f,m \rightarrow f}$ represents distance from the material manufacturing factory to the prefabrication factory, and $d_{f \rightarrow s}$ represents distance between the prefabrication factory to the project site.

Environmental Protection Agency, 2017).

This study provides a valuable reference for decision-makers in developing effective measures to mitigate the influence of various factors on the environmental impacts of optimal multi-use cycle scenarios.

The steel frame and concrete slab are considered the core components of the modular unit, assumed to be repairable but not replaceable. Consequently, changes in the repair rate of these core elements can significantly impact environmental outcomes. In contrast, the steel

Table 1
Scenario analysis of environmental cost and residual value of [15-yr, 25-yr].

Scenario	Description	Environmental cost	Residual value
Baseline	Emission factors (Ecoinvent); Electricity and water consumption: 0 %/yr; Environmental price: HK \$0.86/kg CO ₂ -eq	69725.8	20914.4
1	Electricity: +0.35 %/yr, Water: +0.5 %/yr	72687.7 (+4.2 %)	22037.3 (+5.4 %)
2	Electricity: +0.7 %/yr, Water: +1 %/yr	75887.6.3 (+8.8 %)	23260.0 (+11.2 %)
3	Emission factors (ELCD)	60537.5 (-13.2 %)	18234.2 (-12.8 %)
4	Emission factors (GaBi)	93803.5 (+34.5 %)	28298.2 (+35.3 %)
5	Environmental price: HK\$0.52/kg CO ₂ -eq (Landgraf et al., 2022)	41976.4 (-39.8 %)	20919.6 (0.0 %)
6	Environmental price: HK\$0.71/kg CO ₂ -eq (Eldh and Johansson, 2006)	57304.8 (-17.8 %)	20919.7 (0.0 %)

Note: "+" indicates an increase, while "-" indicates a decrease.

connectors and partition walls are regarded as non-core components, which are assumed to be both replaceable and repairable. Thus, variations in the replacement rate of these components also significantly affect environmental outcomes. In other words, the environmental impact of the core modular components is more sensitive to repair activities, while the impact of subcomponents is more sensitive to replacements, aligning with the findings of Yang et al. (2024). These results suggest that proper maintenance and disassembly procedures should be implemented to prevent damage to both core and non-core modular components during the use and deconstruction phases, thereby minimizing the need for repair and replacement. These suggestions further reinforce the recommendations made by Yang et al. (2024).

Furthermore, this paper finds that the transport distance from material production and prefabrication factories significantly impacts the environmental effects during the production stage of the first life cycle, assuming no new modules are produced in subsequent cycles. This finding aligns with previous studies that have identified the same trend, which is why policymakers and practitioners advocate for the use of local materials and near-site prefabricated components (Jayawardana et al., 2023; Mao et al., 2013). However, the paper also reveals that variations in transport distances among sites, sorting facilities, warehouses, and recycling centres do not significantly affect the environmental cost and residual value of building reuse in later cycles. This suggests that decision-makers have greater flexibility in choosing preferred facilities for repair, replacement, recycling, and temporary storage.

This paper makes a knowledge contribution to resolving a new research problem concerning multi-use cycle scenarios for a demountable modular building system that achieves minimal environmental cost and residual value. Built on established methodologies such as life cycle impact analysis and multi-objective robust optimization, this study presents new findings of optimal multi-use cycle scenarios. Specifically, it identifies that the optimal number of use cycles is two, with the first cycle not exceeding the duration of the second. This research extends existing studies that primarily assess the environmental impacts of building components across multiple use cycles and deepens the understanding of relative environmental savings associated with optimal scenarios, as well as relative environmental burdens linked to non-optimal scenarios. These findings hold practical significance for the construction industry, as the optimal combinations of the number of cycles and duration of cycles can inform decision-makers to develop more sustainable end-of-life strategies for demountable modular building systems.

5.2. Limitations of the study

Despite the knowledge and practical contributions outlined, several limitations should be acknowledged. First, the time-dependent variable for material degradation considered in this LCA is theoretical. While other studies also addressed material degradation or failure rates in the context of building retrofitting or deconstruction (Teng et al., 2024; Mollaei et al., 2023; Xia et al., 2020; Akanbi et al., 2018), these theoretical formulas did not account for external factors such as weather, user behaviour, and labour quality. As a result, the impact of real-time material degradation on the environmental effects of building reuse throughout each cycle remains unexplored. To address this issue, this study attempted to conduct uncertainty and sensitivity analyses of the repair, replacement and reusability of modular components resulting from theoretical material degradation. It has been suggested that combining Monte Carlo simulation with sensitivity analysis can effectively address a wider range of uncertainties (Feng et al., 2022). This approach would enhance the robustness of LCA results (Igos et al., 2019).

Additionally, the monetary factor for carbon dioxide is derived from the Environmental Prices Handbook, which was developed within the European context, reflecting the willingness of European citizens to pay to avoid exposure to environmental pollution. Although both Europe and Hong Kong are considered developed economies, their socio-economic and demographic characteristics differ significantly. It is acknowledged that environmental prices can vary based on regional factors (Amadei et al., 2021). However, Hong Kong currently lacks a comprehensive environmental pricing system. Due to the lack of localized data on monetary factors, this paper relied on globally published data sources, such as Ecoinvent and the Environmental Price Handbook EU28. As a result, the LCA outcomes should be interpreted with caution. To address this issue, scenario analyses were conducted to examine the effects of varying emission factors, monetary factors, and operational resource consumption on the environmental impact of building reuse. The findings revealed that changes in these scenarios significantly influenced the environmental costs and residual value of building reuse. Existing LCA research often encounters challenges due to insufficient localized data, which is why many studies, including this one, incorporate analyses of different scenarios, such as changes in emission factors (Zhang et al., 2019), varied energy consumption (Walker et al., 2022), and different carbon tax rates (Chou and Yeh, 2015).

This study offers new insights into optimal multi-use cycle scenarios for reusing modular units. However, the implications of this research may be limited to specific building typologies and particular use scenarios (Yang et al., 2025). In other words, this study is relevant for building projects that incorporate DfD principles and are technically reusable within their intended lifespan. Additionally, it is applicable to projects with constraints on permanent use, such as land tenancy restrictions and temporary requirements. Furthermore, this study focuses exclusively on environmental impact and the associated environmental cost. To identify optimal multi-use cycle scenarios, future research should conduct a thorough investigation of the financial viability of building assets from a multi-use cycle perspective. The optimization approach should also be expanded to minimize financial costs.

6. Conclusions

This paper addresses a knowledge gap regarding the extent to which the number and duration of cycles can be environmentally sustainable for reusing modular components from a multi-cycling perspective. In the case study of a demountable modular building system in Hong Kong, the study identifies six Pareto-optimal scenarios that combine the number of cycles and the length of each cycle, aimed at minimizing both the environmental costs of embodied and operational carbon emissions and residual value. These scenarios are: [5-yr, 5-yr], [5-yr, 25-yr], [10-yr, 25-yr], [15-yr, 25-yr], [20-yr, 25-yr], and [25-yr, 25-yr]. The results

indicate that the optimal number of cycles is two, and the length of the first use cycle should not be longer than the second one. Additionally, these optimal scenarios indicate that either a shortest (i.e., 10 years) or a longer service life (i.e., more than 30 years). These findings provide valuable insights for decision-makers in developing early end-of-life planning for temporary demountable modular building systems in Hong Kong. The sensitivity analysis of the optimal solution indicates that the variations in value retention activities for certain components and materials (e.g., repair, replacement, and transport) can significantly affect the environmental cost and residual value. The scenario analysis of the optimal solution reveals that the change in emission factors can significantly influence both the environmental cost and residual value of building reuse, while the change in environmental monetary factors has substantial effects on the environmental cost. It is recommended that the financial viability of building reuse over multiple cycles should be examined in the future to identify the optimal reuse scenarios that minimize both environmental and economic impacts.

CRedit authorship contribution statement

Yang Yang: Validation, Formal analysis, Conceptualization, Writing – original draft, Methodology, Data curation. **Bowen Zheng:** Writing – review & editing, Software, Investigation, Data curation, Validation, Methodology, Formal analysis. **Calvin Luk:** Resources, Writing – review & editing, Project administration, Data curation. **Ting Wang:** Writing – review & editing, Supervision, Validation. **Albert Ping-chuen Chan:** Validation, Project administration, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.dibe.2025.100727>.

Data availability

Data will be made available on request.

References

- Abbey, D., Arbabi, H., Gillott, C., Ward, W., Tingley, D.D., 2022. Demolish or reuse? – The balance between operational and embodied emissions in the retrofit of commercial buildings. *IOP Conf. Ser. Earth Environ. Sci.* 1078 (1), 012016. <https://doi.org/10.1088/1755-1315/1078/1/012016>.
- Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resour. Conserv. Recycl.* 129, 175–186. <https://doi.org/10.1016/j.resconrec.2017.10.026>.
- Akande, O.K., Odeleye, D., Coday, A., JimenezBescos, C., 2016. Performance evaluation of operational energy use in refurbishment, reuse, and conservation of heritage buildings for optimum sustainability. *Frontiers of Architectural Research* 5 (3), 371–382. <https://doi.org/10.1016/j.foar.2016.06.002>.
- Akbarnezhad, A., Ong, K.C.G., Chandra, L.R., 2014. Economic and environmental assessment of deconstruction strategies using building information modeling. *Autom. ConStruct.* 37, 131–144. <https://doi.org/10.1016/j.autcon.2013.10.017>.
- Amadei, A.M., De Laurentiis, V., Sala, S., 2021. A review of monetary valuation in life cycle assessment: state of the art and future needs. *J. Clean. Prod.* 329, 129668. <https://doi.org/10.1016/j.jclepro.2021.129668>.
- Antwi-Afari, P., Ng, S.T., Chen, J., Oluleye, B.I., Antwi-Afari, M.F., Ababio, B.K., 2023. Enhancing life cycle assessment for circular economy measurement of different case scenarios of modular steel slab. *Build. Environ.* 239, 110411. <https://doi.org/10.1016/j.buildenv.2023.110411>.
- Arrigoni, A., Marveggio, D., Allievi, F., Dotelli, G., Scaccabarozzi, G., 2023. Environmental and health-related external costs of meat consumption in Italy: estimations and recommendations through life cycle assessment. *Sci. Total Environ.* 869, 161773. <https://doi.org/10.1016/j.scitotenv.2023.161773>.
- Baldoni, E., Coderoni, S., D'Orazio, M., Di Giuseppe, E., Esposti, R., 2019. The role of economic and policy variables in energy-efficient retrofitting assessment. A stochastic Life Cycle Costing methodology. *Energy Policy* 129, 1207–1219. <https://doi.org/10.1016/j.enpol.2019.03.018>.
- Bertin, I., Saadé, M., Le Roy, R., Jaeger, J.-M., Feraille, A., 2022. Environmental impacts of Design for Reuse practices in the building sector. *J. Clean. Prod.* 349, 131228. <https://doi.org/10.1016/j.jclepro.2022.131228>.
- Brütting, J., Vandervaeren, C., Senatore, G., De Temmerman, N., Fivet, C., 2020. Environmental impact minimization of reticular structures made of reused and new elements through Life Cycle Assessment and Mixed-Integer Linear Programming. *Energy Build.* 215, 109827. <https://doi.org/10.1016/j.enbuild.2020.109827>.
- Chen, L.-K., Yuan, R.-P., Ji, X.-J., Lu, X.-Y., Xiao, J., Tao, J.-B., Kang, X., Li, X., He, Z.-H., Quan, S., Jiang, L.-Z., 2021. Modular composite building in urgent emergency engineering projects: a case study of accelerated design and construction of Wuhan Thunder God Mountain/Leishenshan hospital to COVID-19 pandemic. *Autom. ConStruct.* 124, 103555. <https://doi.org/10.1016/j.autcon.2021.103555>.
- Chileshe, N., Jayasinghe, R.S., Rameezdeen, R., 2019. Information flow-centric approach for reverse logistics supply chains. *Autom. ConStruct.* 106, 102858. <https://doi.org/10.1016/j.autcon.2019.102858>.
- Chou, J.-S., Yeh, K.-C., 2015. Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction. *J. Clean. Prod.* 101, 137–147. <https://doi.org/10.1016/j.jclepro.2015.04.001>.
- Clough, I., 2022. The case for more modular facilities in the NHS. *Br. J. Healthc. Manag.* 28 (Suppl. 3), 3–11. <https://doi.org/10.12968/bjhc.2021.0104>.
- Construction Industry Council, 2022. Heavy lifting operation for MiC projects reference material. www.cic.hk.
- De Bruyn, S., Ahdour, S., Bijleveld, M., De Graaff, L., Schep, E., Schroten, A., Vergeer, R., 2018. *Environmental Prices Handbook* 2018.
- De Vries, J., De Bruyn, S., Boerdijk, S., Juijn, D., Bijleveld, M., Van Der Giesen, C., Korteland, M., Odenhoven, N., Van Santen, W., Pápai, S., 2024. *Environmental prices Handbook 2024: EU27 version*. www.ce.nl.
- De Wolf, C., Hoxha, E., Fivet, C., 2020. Comparison of environmental assessment methods when reusing building components: a case study. *Sustain. Cities Soc.* 61. <https://doi.org/10.1016/j.scs.2020.102322>.
- Drewniok, M.P., Dunant, C.F., Allwood, J.M., Ibell, T., Hawkins, W., 2023. Modelling the embodied carbon cost of UK domestic building construction: today to 2050. *Ecol. Econ.* 205, 107725. <https://doi.org/10.1016/j.ecolecon.2022.107725>.
- Eberhardt, L.C.M., Birgisdóttir, H., Birkved, M., 2019. Life cycle assessment of a Danish office building designed for disassembly. *Build. Res. Inf.* 47 (6), 666–680. <https://doi.org/10.1080/09613218.2018.1517458>.
- Eldh, P., Johansson, J., 2006. Weighting in LCA based on ecotaxes - development of a mid-point method and experiences from case studies. *Int. J. Life Cycle Assess.* 11 (S1), 81–88. <https://doi.org/10.1065/lca2006.04.015>.
- Electrical and Mechanical Services Department, 2024. Hong Kong energy end-use data. <https://www.emsd.gov.hk/filemanager/en/content/762/HKEEUD2024.pdf>.
- European Union, 2022. EU provides temporary modular housing for families displaced to Chernivtsi following the full-scale Russian invasion. <https://www.eeas.europa.eu/delegations/ukraine/eu-provides-temporary-modular-housing-families-displaced-chernivtsi-following-en>.
- Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., Thurairajah, N., 2022. Uncertainties in whole-building life cycle assessment: A systematic review. *J. Build. Eng.* 50, 104191. <https://doi.org/10.1016/j.jobee.2022.104191>.
- Galimshina, A., Moustapha, M., Hollberg, A., Padey, P., Lasvaux, S., Sudret, B., Habert, G., 2021. What is the optimal robust environmental and cost-effective solution for building renovation? Not the usual one. *Energy Build.* 251, 111329. <https://doi.org/10.1016/j.enbuild.2021.111329>.
- Goedkoop, M.J., 2008. ReCiPe 2008: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. <https://www.researchgate.net/publication/302559709>.
- Grosso, M., Thiebat, F., 2015. Life cycle environmental assessment of temporary building constructions. *Energy Proc.* 78, 3180–3185. <https://doi.org/10.1016/j.egypro.2015.11.777>.
- Guo, X., Xie, Y., Xiao, P., Ma, Z., Zhao, H., Li, G., Du, H., Lv, Y., 2023. Life cycle and environmental cost assessment of ultrasound-assisted alkaline extraction of hemicellulose by sugarcane bagasse pith. *J. Clean. Prod.* 412, 137420. <https://doi.org/10.1016/j.jclepro.2023.137420>.
- Hossain, Md U., Ng, S.T., Antwi-Afari, P., Amor, B., 2020. Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction. *Renew. Sustain. Energy Rev.* 130, 109948. <https://doi.org/10.1016/j.rser.2020.109948>.
- Housing Bureau, 2024. Transitional housing projects. <https://www.hb.gov.hk/eng/policy/housing/policy/transitionalhousing/transitionalhousing.html#:~:text=Summary>

- %20of%20Transitional%20Housing%20Projects,accommodation%20for%20those%20in%20need.
- Huang, Z., Chen, Y., Shen, L., Huang, Y., Li, S., 2021. An improved stochastic life-cycle cost analysis model for examining the impact of environmental policy instruments on construction equipment replacement. *Environ. Impact Assess. Rev.* 90, 106627. <https://doi.org/10.1016/j.eiar.2021.106627>.
- Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A., 2013. Operational vs. embodied emissions in buildings—a review of current trends. *Energy Build.* 66, 232–245. <https://doi.org/10.1016/j.enbuild.2013.07.026>.
- Igos, E., Benetto, E., Meyer, R., Baustert, P., Othoniel, B., 2019. How to treat uncertainties in life cycle assessment studies? *Int. J. Life Cycle Assess.* 24 (4), 794–807. <https://doi.org/10.1007/s11367-018-1477-1>.
- Incelli, F., Cardellicchio, L., Rossetti, M., 2023. Circularity indicators as a design tool for design and construction strategies in architecture. *Buildings* 13 (7), 1706. <https://doi.org/10.3390/buildings13071706>.
- Jayasena, A., Hewage, K., Siddiqui, O., Sadiq, R., 2022. Socio-economic and environmental cost-benefit analysis of passive houses: a life cycle perspective. *J. Clean. Prod.* 373, 133718. <https://doi.org/10.1016/j.jclepro.2022.133718>.
- Jayawardana, J., Sandanayake, M., Jayasinghe, J.A.S.C., Kulatunga, A.K., Zhang, G., 2023. A comparative life cycle assessment of prefabricated and traditional construction – a case of a developing country. *J. Build. Eng.* 72, 106550. <https://doi.org/10.1016/j.jobe.2023.106550>.
- Jiang, L., Li, Y., Cai, Y., Liu, K., Liu, C., Zhang, J., 2022. Probabilistic health risk assessment and monetization based on benzene series exposure in newly renovated teaching buildings. *Environ. Int.* 163, 107194. <https://doi.org/10.1016/j.envint.2022.107194>.
- Kang, G., Kim, T., Kim, Y.-W., Cho, H., Kang, K.-I., 2015. Statistical analysis of embodied carbon emission for building construction. *Energy Build.* 105, 326–333. <https://doi.org/10.1016/j.enbuild.2015.07.058>.
- Landgraf, M., Zeiner, M., Knabl, D., Corman, F., 2022. Environmental impacts and associated costs of railway turnouts based on Austrian data. *Transport. Res. Transport Environ.* 103, 103168. <https://doi.org/10.1016/j.trd.2021.103168>.
- Lei, H., Yang, W., Zhang, B., Li, C.-Q., 2025. An advanced method for assessing circular economy performance of built environment. *J. Clean. Prod.* 486, 144561. <https://doi.org/10.1016/j.jclepro.2024.144561>.
- Liang, Y., Pan, Y., Yuan, X., Yang, Y., Fu, L., Li, J., Sun, T., Huang, Z., Kosonen, R., 2022. Assessment of operational carbon emission reduction of energy conservation measures for commercial buildings: model development. *Energy Build.* 268, 112189. <https://doi.org/10.1016/j.enbuild.2022.112189>.
- Local Government Association, 2021. Relocatable modular homes in dorset for adult social care clients. <https://www.local.gov.uk/case-studies/adult-social-care-provisi-on-dorset-building-better-lives-programme>.
- Lu, K., Deng, X., 2023. OpenBIM-based assessment for social cost of carbon through building life cycle. *Sustain. Cities Soc.* 99, 104871. <https://doi.org/10.1016/j.scs.2023.104871>.
- Luk, C., Yang, Y., Chung, K.-F., Shen, J., Jia, Y., Bowen, Z., Eric, Y., Wilson, C., Thomas, T., Eric, J., 2023. Technical Report on Deconstruction, Relocation and Reinstallation of Nam Cheong 220 Transitional Housing.
- Luo, W., Zhang, Y., Gao, Y., Liu, Y., Shi, C., Wang, Y., 2021. Life cycle carbon cost of buildings under carbon trading and carbon tax system in China. *Sustain. Cities Soc.* 66, 102509. <https://doi.org/10.1016/j.scs.2020.102509>.
- Mao, C., Shen, Q., Shen, L., Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects. *Energy Build.* 66, 165–176. <https://doi.org/10.1016/j.enbuild.2013.07.033>.
- Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L., 2020. Exploring environmental benefits of reuse and recycle practices: a circular economy case study of a modular building. *Resour. Conserv. Recycl.* 160. <https://doi.org/10.1016/j.resconrec.2020.104855>.
- Mollaei, A., Bachmann, C., Haas, C., 2023. Estimating the recoverable value of in-situ building materials. *Sustain. Cities Soc.* 91, 104455. <https://doi.org/10.1016/j.scs.2023.104455>.
- Nasr, N., Russell, J., Bringezu, S., Hellweg, S., Hilton, B., Kreiss, C., von Gries, N., 2018. A Report of the International Resource Panel. United Nations Environment Programme.
- National Health Service, 2024. Modular buildings. <https://www.sbs.nhs.uk/services/framework-agreements/modular-buildings/>.
- Nydahl, H., Andersson, S., Åstrand, A.P., Olofsson, T., 2019. Including future climate induced cost when assessing building refurbishment performance. *Energy Build.* 203, 109428. <https://doi.org/10.1016/j.enbuild.2019.109428>.
- Nydahl, H., Andersson, S., Åstrand, A.P., Olofsson, T., 2022. Extended building life cycle cost assessment with the inclusion of monetary evaluation of climate risk and opportunities. *Sustain. Cities Soc.* 76, 103451. <https://doi.org/10.1016/j.scs.2021.103451>.
- Obrecht, T.P., Jordan, S., Legat, A., Ruschi Mendes Saade, M., Passer, A., 2021. An LCA methodology for assessing the environmental impacts of building components before and after refurbishment. *J. Clean. Prod.* 327, 129527. <https://doi.org/10.1016/j.jclepro.2021.129527>.
- Pandey, M.D., van der Weide, J.A.M., 2017. Stochastic renewal process models for estimation of damage cost over the life-cycle of a structure. *Struct. Saf.* 67, 27–38. <https://doi.org/10.1016/j.strusafe.2017.03.002>.
- Pannier, M.-L., Schallbart, P., Peuportier, B., 2018. Comprehensive assessment of sensitivity analysis methods for the identification of influential factors in building life cycle assessment. *J. Clean. Prod.* 199, 466–480. <https://doi.org/10.1016/j.jclepro.2018.07.070>.
- Phuang, Z.X., Mulya, K.S., Hoy, Z.X., Woon, K.S., 2023. Moving towards plastic waste circularity: redefining extended producer responsibility with externality consideration via P-graph-life cycle optimization framework. *Resour. Conserv. Recycl.* 198, 107187. <https://doi.org/10.1016/j.resconrec.2023.107187>.
- Russell, J., Nasr, N., 2019. Value-retention processes within the circular economy. In: *Remanufacturing in the Circular Economy*. Wiley, pp. 1–29. <https://doi.org/10.1002/9781119664383.ch1>.
- Saleh, L., Zaabi, M. al, Mezher, T., 2019. Estimating the social carbon costs from power and desalination productions in UAE. *Renew. Sustain. Energy Rev.* 114, 109284. <https://doi.org/10.1016/j.rser.2019.109284>.
- Sobol', I.M., 2001. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Math. Comput. Simulat.* 55 (1–3), 271–280. [https://doi.org/10.1016/S0378-4754\(00\)00270-6](https://doi.org/10.1016/S0378-4754(00)00270-6).
- Sobotka, A., Czaja, J., 2015. Analysis of the factors stimulating and conditioning application of reverse logistics in construction. *Procedia Eng.* 122, 11–18. <https://doi.org/10.1016/j.proeng.2015.10.002>.
- Tan, T., Mills, Grant, Hu, Jiqiang, Papadonikolaki, E., 2021. Integrated approaches to design for manufacture and assembly: a case study of huoshenshan hospital to combat COVID-19 in wuhan, China. [https://doi.org/10.1061/\(ASCE\)ME.1943](https://doi.org/10.1061/(ASCE)ME.1943).
- Teng, Y., Li, Z., Li, T., Li, Y., Gong, E., Tiong, R.L.K., Liu, S., 2024. Regeneration diagnosis for the service lifespans of residential buildings on a circular economy perspective. *Energy Build.* 319, 114536. <https://doi.org/10.1016/j.enbuild.2024.114536>.
- Tol, R.S.J., 2005. The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. *Energy Policy* 33 (16), 2064–2074. <https://doi.org/10.1016/j.enpol.2004.04.002>.
- UNECE, 2021. Housing for Migrants and Refugees in the UNECE Region Challenges and Practices.
- US Environmental Protection Agency, 2017. The social cost of carbon. <https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon.html>.
- van Stijn, A., Eberhardt, L.C.M., Wouterszoon Jansen, B., Meijer, A., 2022. Environmental design guidelines for circular building components based on LCA and MFA: lessons from the circular kitchen and renovation façade. *J. Clean. Prod.* 357, 131375. <https://doi.org/10.1016/j.jclepro.2022.131375>.
- van Stijn, A., Malabi Eberhardt, L.C., Wouterszoon Jansen, B., Meijer, A., 2021. A circular economy life cycle assessment (CE-LCA) model for building components. *Resour. Conserv. Recycl.* 174, 105683. <https://doi.org/10.1016/j.resconrec.2021.105683>.
- Walker, L., Hischier, I., Schlueter, A., 2022. Scenario-based robustness assessment of building system life cycle performance. *Appl. Energy* 311, 118606. <https://doi.org/10.1016/j.apenergy.2022.118606>.
- Wang, J., Wei, J., Zhang, W., Liu, Z., Du, X., Liu, W., Pan, K., 2022. High-resolution temporal and spatial evolution of carbon emissions from building operations in Beijing. *J. Clean. Prod.* 376, 134272. <https://doi.org/10.1016/j.jclepro.2022.134272>.
- Wang, J., Zhang, Y., Wang, Y., 2018. Environmental impacts of short building lifespans in China considering time value. *J. Clean. Prod.* 203, 696–707. <https://doi.org/10.1016/j.jclepro.2018.08.314>.
- Water Supplies Department, 2015. Household water use survey. https://www.wsd.gov.hk/filemanager/sc/content_1472/factsheet_c_2015.pdf.
- Wen, X., Teng, Y., Shen, G.Q., 2024. Extended end-of-life carbon assessment and savings: a case study of steel-framed modular buildings in Hong Kong. *Build. Environ.* 266, 112056. <https://doi.org/10.1016/j.buildenv.2024.112056>.
- Xia, B., Ding, T., Xiao, J., 2020. Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study. *Waste Manage* 105, 268–278. <https://doi.org/10.1016/j.wasman.2020.02.015>.
- Yang, Y., Luk, C., Zheng, B., Hu, Y., Chan, A.P.-C., 2025. Disassembly and reuse of demountable modular building systems. *J. Manag. Eng.* 41 (1). <https://doi.org/10.1061/JMENA.MEENG-6243>.
- Yang, Y., Zheng, B., Luk, C., Yuen, K., Chan, A., 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. <https://doi.org/10.1016/j.spc.2024.02.027>.
- Zhang, R., Wang, Q., Shen, H., Yang, Y., Liu, P., Dong, Y., 2024. Environmental benefits of macroalgae products: a case study of agar based on life cycle assessment. *Algal Res.* 78, 103384. <https://doi.org/10.1016/j.algal.2023.103384>.
- Zhang, X., Zheng, R., Wang, F., 2019. Uncertainty in the life cycle assessment of building emissions: a comparative case study of stochastic approaches. *Build. Environ.* 147, 121–131. <https://doi.org/10.1016/j.buildenv.2018.10.016>.
- Zheng, B., Yang, Y., Chi, H.-L., Luk, C., Chan, A., 2025. Development of a BIM-based application for visualizing the reuse and recycling potential of modular building systems. *J. Build. Eng.* 105, 112500. <https://doi.org/10.1016/j.jobe.2025.112500>.