Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

"Design-In Waste" for circular architecture: a conceptual framework

Bing YANG*, Weisheng LU, Liang YUAN

* Department of Real Estate and Construction, Faculty of Architecture, University of Hong Kong
KB714, Knowles Building, Pokfulam, University of Hong Kong
yangbing@connect.hku.hk

Abstract

Contemporary architectural discourse is increasingly focused on "designing out" construction waste early in the design process to enhance building lifecycle circularity. However, there's a growing trend towards integrating existing building components and materials into new designs to further this goal. This paper presents a multilevel conceptual framework that prioritizes "design-in" waste as a fundamental aspect of circular architecture, demonstrated through a case study of a demolished residence building at the University of Hong Kong (HKU). The study examines traditional demolition processes, identifying the types and volumes of waste produced, and reevaluates the potential for reusing demolished components. By applying the Design-In Waste framework, it explores strategies for the disassembly and future use of these materials, challenging the construction industry to shift from demolition to deconstruction. This approach not only highlights the practical challenges of implementing such a transition but also showcases how sustainable and circular construction practices can be operationalized, paving the way for buildings with enhanced lifecycle circularity.

Keywords: circular architecture; material reuse; design-in waste; sustainable design; case study

1. Introduction

The construction industry plays a vital role in economic development. However, it is also a significant contributor to environmental problems due to its substantial resource consumption and waste generation [1]. The construction process often leads to unnecessary waste, such as over-ordering supplies and mishandling materials [2]. Moreover, building demolition, which is not always necessitated by structural aging or deterioration, can produce even more avoidable waste and pollution. More often than not, buildings meet their premature end, and structurally functional and integral components and elements are reduced to rubble [3]. The waste generated from construction activities, including new construction, renovation, demolition, site clearance, and excavation, is commonly referred to as "construction waste" or "construction and demolition waste" [4].

As the environmental crises deepen, construction waste management (CWM) has evolved into a comprehensive spectrum, including the collection, sorting, transportation, reuse, recycling, landfilling, and resource recovery of waste materials [5]. However, as an end product and a catalyst of the linear economic growth model, which prioritizes production and consumption over sustainability, current demolition practices often favor speed and cost-efficiency over environmental considerations [6]. While recycling aims to remedy the environmental impact by converting construction waste into new materials, the process itself is energy and carbon-emission intensive, often requiring the transportation of waste to specialized facilities and the use of heavy industrial processes [7]. These challenges underscore the need for a more circular approach to the built environment, from architectural design to construction waste management, one that prioritizes the reuse of waste components without drastically altering their original form.

This paper presents the "design-in-waste" framework and demonstrates its application through a case study of a demolished building in Hong Kong. The paper is structured as follows: Section 2 provides a literature review on construction waste management, circular economy, and the "design-in-waste" framework; Section 3 outlines the methodology employed in the study; Section 4 presents the current status of demolition practices in Hong Kong via the case study; Section 5 discusses the implementation of the design-in-waste framework in the context of the case study; Section 6 examines the findings and limitations of the study; and Section 7 concludes with recommendations for future research and practice.

2. Theoretical background and conceptual framework

The past decade has seen a rise in discussions centering on the circular economy (CE) as a response to environmental deterioration and resource depletion. MacArthur[8] defines CE as "an industrial system that is restorative or regenerative by intention and design." The various attempts to incorporate CE principles in the built environment have seen significant advancements, integrating digital technologies such as open-BIM, digital twins, material passports, blockchain, RFID, and gamification, which facilitate the tracking, management, and reuse of building materials and components [9]. Nevertheless, there remains an undeniable gap between these digital advancements and the implementation of CE principles in urban design and architectural practice. The insights gained from research need to be translated into tangible projects, building norms, and codes. For example, architects can leverage material passports to design buildings with components that can be easily disassembled, facilitating future reuse and reducing waste [10]. Architects should play a central role in bridging the gap between research and practice, driving the transition towards a more circular built environment.

The "design-in-waste" conceptual framework can be regarded as a further development of "designing out waste," one of the core principles of the circular economy, which emphasizes designing products for a cycle of disassembly and reuse to minimize waste generation [8]. The first step of "design in waste" is to view end-of-life buildings as valuable resources instead of burdens, recognizing the potential for their components and materials to be repurposed, thereby reducing waste and preserving the embodied energy of these elements. The next step is to integrate the deconstructed components and elements into new designs, using design for disassembly and design by availability as guidelines. The framework entails a three-fold consideration: the formal perspective, in terms of components' aesthetic and structural potential; the methodological perspective, in terms of construction and deconstruction techniques' feasibility; and the external perspective, in terms of environmental sustainability and social implications. By adopting the "design in waste" approach, architects and designers can play a crucial role in promoting a more sustainable and circular built environment, minimizing waste, and optimizing the use of existing resources.

The implementation of the "design-in-waste" framework can lead to several potential benefits. First and foremost, it recognizes the importance of design as the convergence point of knowledge and ideas from different disciplines [11]. By fully exercising their potential as agents of change, architects can foster the circularity of construction through this framework. The framework also has the potential to achieve significant waste reduction and resource conservation, minimizing the environmental impact of construction activities. Moreover, the reuse of building components and elements can contribute to local cultural identity construction and community building. As a matter of fact, there has been a significant cultural meaning in the reuse of architectural components throughout the history of architecture [12]. By incorporating familiar or historically significant elements into new designs, architects can create a sense of place and engage the community in the process of urban transformation. This approach not only promotes sustainability but also strengthens the social fabric of the built environment.

3. Methodology

This study employs a case study approach, focusing on the demolition of the HKU residence blocks on Pokfield Road, Hong Kong. Completed in 1960, these concrete beam-column frame structures are representative of common building types and demolition practices in Hong Kong, making them suitable for examining the application of the design-in Waste framework.

Data on the demolition waste from the HKU residence blocks was collected using Hong Kong's Construction Waste Disposal Charging Scheme (CWDCS). For any construction work under a contract with a value of 1,000,000 HKD or above, contractors must open a dedicated billing account [13]. By associating the billing account to different government waste disposal facilities, we are able to determine the waste types, quantities, and transportation routes, enabling us to estimate the environmental impact of the demolition work.

Following the analysis of the demolition practice and its environmental impact, we apply the Design-In Waste framework to the case study to demonstrate the potential for transitioning from demolition to deconstruction and reuse. The framework consists of three key aspects: deconstruction instead of demolition, design for disassembly, and design by availability. As a first step, we reconstructed a 3D model of the building blocks using ArchiCAD software and the demolition plan [14]. According to the method statement, non-structural elements such as furniture, wood floors, door frames, windows, and building services were removed prior to demolition. Consequently, the model focused on structural components, which were categorized into exterior walls, slabs, interior walls, columns, and staircases, enabling the identification and quantification of potentially reusable elements.

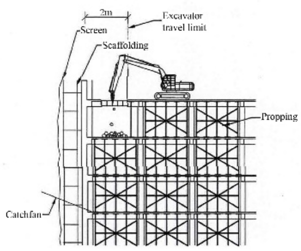
The next step is to explore the design for disassembly potential of the identified components. This involves assessing the necessary alterations to the components' shape and dimensions to facilitate their retrieval during the deconstruction process. For instance, floor slabs should be cut along the beams, corresponding to the interior walls, to enable their removal. Furthermore, the redesign of joints is crucial to ensure that the retrieved components can be easily reassembled and disassembled in future applications. This process involves developing innovative connection methods that prioritize reversibility and adaptability, allowing for the efficient reuse of the salvaged components in new construction projects.

Hypothetical reuse scenarios for the salvaged components are developed in the context of the Pokfield campus development project, which replaces the demolished residence blocks. The scenarios utilize the design by availability approach, attempting to maximize the use of accessible elements within a local range. For the hypothetical reuse in the Pokfield campus project, we consider the potential for incorporating concrete panels, columns, and beams into the construction of new infrastructure and landscaping features. Limitations and uncertainties in the scenario development process are discussed, addressing aspects such as data availability and underlying assumptions.

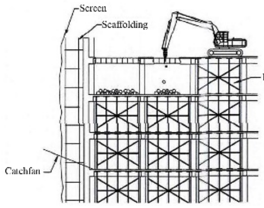
4. A case study in the demolition practices

The case study starts from the demolition of three 6-storey residence blocks at Pokfield Road. Completed in 1960, the buildings belong to the University of Hong Kong. Each block has a footprint of approximately 17m by 13m and an overall height of 23m, with a typical floor height of 2.9m [14]. The main structural system is a reinforced concrete column-beam frame, which is representative of the construction methods used in Hong Kong during that era.

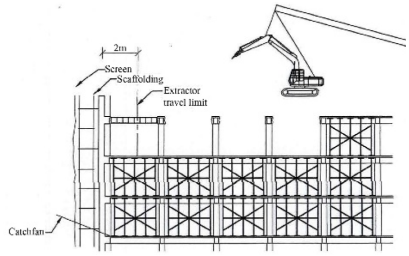
The demolition is carried out using three mechanical plants, one for each block. Prior to the commencement of demolition, all non-structural elements are removed. The work starts from the roof floor and proceeds one floor at a time. The structure is demolished in the sequence of the perimeter wall, slab, beam, and then internal walls or columns. The buildings are ultimately demolished down to the existing ground profile, with the foundation basement remaining in place. According to the CWDCS records, the waste disposal for this project spans from April 28th, 2021, to August 1st, 2022, with a total duration of 460 days.



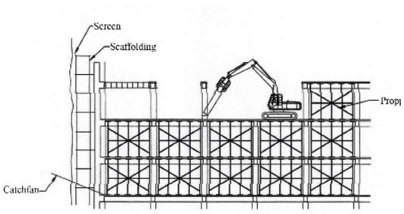
1. Demolition of slabs and beams



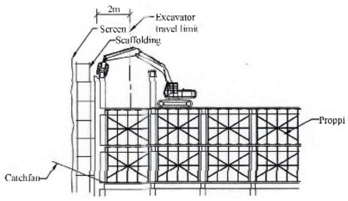
2. Continue demolition of slabs and beams



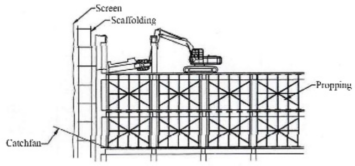
3. Mobile crane stationed on ground will be used to lift the machine down to the next floor below



4. Demolition of interior column may be needed to create access and working room for exterior wall demolition. Demolish column by first pre-weakening the bottom, then dismantled by machine in fully controlled motion.



5. Cutting the exterior wall in sections and pre-weakening of columns. Cutting should be careful to minimize debris falling outside.



6. Machine should be used to brace the wall section while cutting the reinforcing bars connecting the wall section. The wall section shall be pulled down in a controlled motion.

Figure 1. Typical sequence of demolition with mechanical equipment, adapted from [14]

Figure 2. Demolition site photo

According to the EPD regulations, construction waste in Hong Kong is classified as either inert or non-inert. Inert construction waste includes rock, rubble, boulder, earth, soil, sand, concrete, asphalt, brick, tile, masonry, or used bentonite, while non-inert waste contains bamboo, plastics, glass, wood, paper, vegetation, and other organic materials [13]. The demolition of the HKU residence buildings generated a total of approximately 18,148 tonnes of construction waste. This waste was transported to various facilities across Hong Kong, including public fill reception facilities, sorting facilities, and landfills. Public fill reception facilities, which accept entirely inert waste, received the majority of the waste (17,782.88 tonnes). Sorting facilities, which accept waste containing more than 50% inert content, received 206.56 tonnes, while landfills, which accept waste with no more than 50% inert content, received 158.91 tonnes. Based on the waste transportation data and the estimated distance to each facility, the carbon emissions generated from the transportation of waste to these facilities are estimated to be between 26 and 48 tonnes, further contributing to the overall environmental impact of the demolition process.

Based on the waste distribution data and assumptions about waste composition in sorting facilities and landfills, it is estimated that 98.99% (17,965.62 tonnes) of the total waste generated from the demolition project was inert, while 1.01% (182.74 tonnes) was non-inert. From this classification itself, alongside the statistics regarding the waste, we can see that conventional demolition practices prioritize the rapid and complete destruction of the structures, resulting in the generation of a significant amount of waste, primarily in the form of rubble. The findings underscore the need for a shift in demolition practices, moving away from the current demolition paradigm and towards a more selective and systematic deconstruction approach that facilitates the recovery and reuse of building materials. This shift aligns with the principles of the Design-in Waste framework, which will be explored in the next section as a potential solution to the identified shortcomings in current demolition practices.

5. Application of the design-in waste framework

5.1 Reusable components estimation

The design-in-waste framework begins with estimating reusable components from buildings at the end of life. This process involves a thorough assessment of the building's components and their potential for salvage and reuse. In the case study of the demolished HKU residence buildings, a comprehensive analysis was conducted to identify and quantify the reusable components.

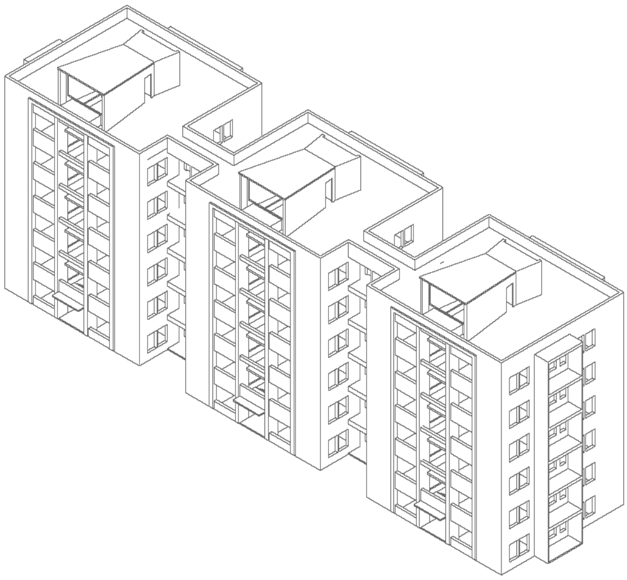


Figure 3. Axonometric view of the three HKU residence blocks

The methodology employed in this analysis involved a detailed examination of the building's structural system, which consisted of reinforced concrete columns, beams, slabs, and walls. As the buildings were demolished between 2021 and 2022, the assessment was based on the original architectural and structural drawings, as well as the demolition plan. A 3D model of the building was reconstructed using ArchiCAD software, and the reusable components were categorized according to their type, dimensions, and quantity. Admittedly, there might be damaged components not suitable for reuse; however, due to the data limitation, we will solely focus on the categorization of the components in this study.

The results of the estimation revealed a significant potential for salvaging and reusing building components from the HKU residence buildings. As shown in Figure 4, the reusable components included:

- Reinforced concrete columns: 216 units, each 2.92 m in height
- Main beams: 306 units, ranging from 2.02 m to 5.66 m in length
- Secondary beams: 252 units, ranging from 2.30 m to 6.12 m in length
- Reinforced concrete wall panels: 258 units, ranging from 1.35 m to 5.06 m in length and 2.92 m in height
- Reinforced concrete slabs: 434 units, ranging from 1.78 m^2 to 13.73 m^2 in area

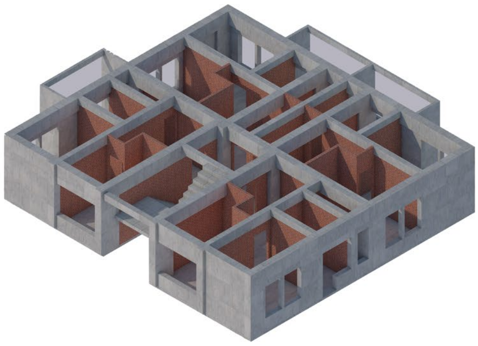


Figure 4. Typical floor layout of a single residence block

The estimation of reusable components provides a foundation for the subsequent steps in the design-in-waste framework, namely Design for Disassembly and Design by Availability. By identifying and quantifying the reusable components, architects and designers can make informed decisions about how to incorporate these elements into new projects, promoting a more sustainable and circular approach to construction.

5.2 Design for Disassembly

The next step in the design-in-waste framework is to address the question of how to properly reuse the salvaged components. The dismantled components need to be rejoined in a way that satisfies the structural demand and aesthetic need, and they must be easily dismantled again for the next cycle. Therefore, the design for disassembly (DfD) principle is a crucial component of the design-in waste framework, aiming to develop connection joint solutions that facilitate the easy assembly and disassembly of salvaged building components. In the context of the HKU residence building case study, the application of DfD involves designing horizontal and vertical connection joints that accommodate the reuse of components in various configurations.

We opted to categorize the connection joints as horizontal and vertical rather than following the specific component types in the deconstruction scenario, that is, beams, columns, wall panels, and so on. This approach acknowledges that the original function of a salvaged component may not necessarily dictate its future use. As a matter of fact, the component usage often times alters in the next life cycle [15]. This flexibility promotes a more adaptable and efficient reuse strategy, maximizing the potential for incorporating salvaged components into new construction projects.

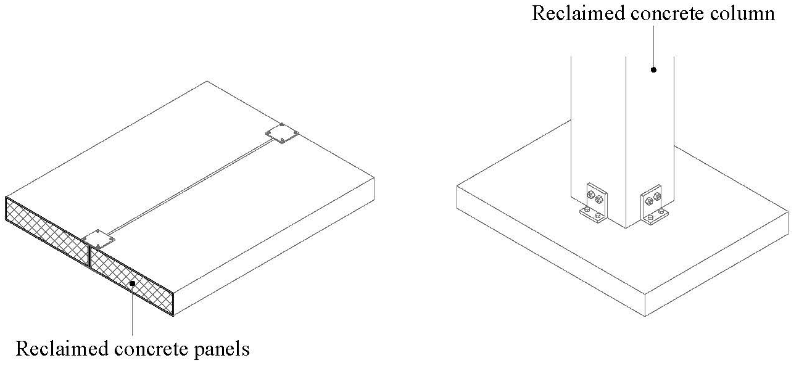


Figure 5: examples of horizontal and vertical connection joints

The horizontal connection joint designs focus on the linear connection between salvaged components, such as wall panels or floor slabs, allowing for various configurations and adaptations. These joints utilize steel profiles and bolted connections to create a secure yet reversible bond between the components. The profiles can be arranged in different ways, such as end-to-end, overlapping, or with additional connecting elements, depending on the specific requirements of the project and the dimensions of the salvaged components. The vertical connection joint designs employ steel plates and bolts to create a strong yet reversible connection between stacked components, such as columns or wall panels. These joints ensure the structural stability of the assembled components while allowing for easy disassembly when needed.

By incorporating these generic horizontal and vertical connection joint designs, the DfD approach enables a wide range of salvaged components to be reused in new construction projects, regardless of their original function or dimensions. This flexibility is crucial for maximizing the potential of the design-in-waste framework and promoting a more sustainable and circular construction industry. However, it is important to acknowledge that the use of steel in these connection joints may have its own environmental impact, as steel production is energy-intensive and contributes to carbon emissions [16]. Future research should explore alternative materials or optimize the design of steel connections to minimize their environmental footprint while maintaining their structural performance and reversibility.

5.3 Design by Availability

The design-by-availability concept is an integral part of the design-in-waste framework. This principle emphasizes the utilization of readily available salvaged components in the design process, or, as the sample project Recylinghaus claims, "form follows availability" [17]. In the context of the HKU residence building case study, design by availability involves exploring how the salvaged components can be creatively incorporated into new projects.

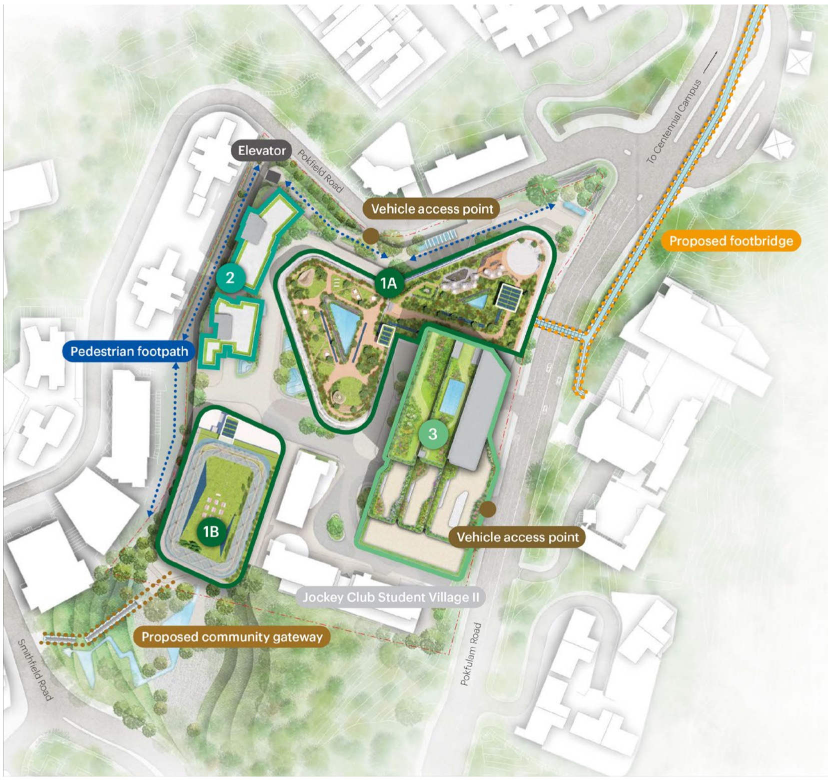


Figure 6: Master plan of the HKU Pokfield Campus Development project

The demolition of the HKU residence buildings at Pokfield Road paves the way for the Pokfield Campus Development. It is a transformative project by HKU, aiming to expand the university's facilities into an iconic hub with an emphasis on environmental benefits and green open spaces (Figure 6). A key feature of the project is the proposed footbridge, which enhances pedestrian connectivity by linking the campus to adjacent areas. In an alternative scenario where the HKU residence buildings were deconstructed rather than demolished, the reclaimed concrete panels, columns, and beams could have been invaluable resources for the footbridge construction.

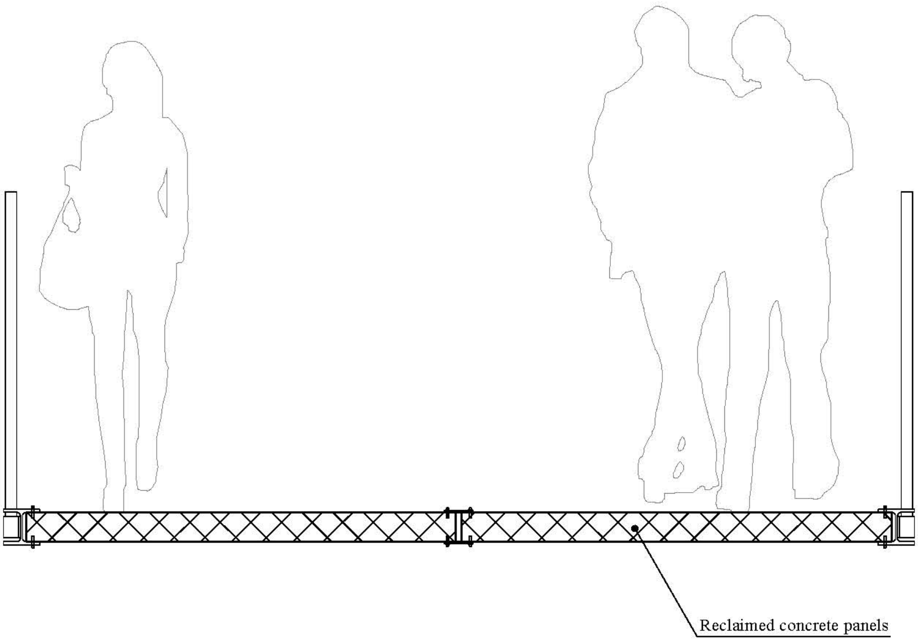


Figure 7: Conceptual design of the footbridge utilizing reclaimed concrete panels

The footbridge design could have incorporated the reclaimed concrete panels as the primary structural elements, coupled with steel joints to accommodate the specific dimensions and structural properties of the panels. This modular construction technique would not only promote sustainability but also showcase the potential for creative reuse of salvaged components. Moreover, with proper joints, the concrete panels could be reconfigured into arches, offering an alternative to conventional flat walkways and enriching the spatial experience.

In addition to the footbridge, the salvaged components could have been repurposed for outdoor pavements and communal spaces within the new campus. The reclaimed wall panels, with their intrinsic architectural features such as window or door openings, could have been adapted to integrate greenery, promoting biodiversity in the urban fabric. Similarly, the transformation of reclaimed beams into benches would have contributed to the social and communal aspects of the campus environment while embodying the principles of sustainability and material reuse.

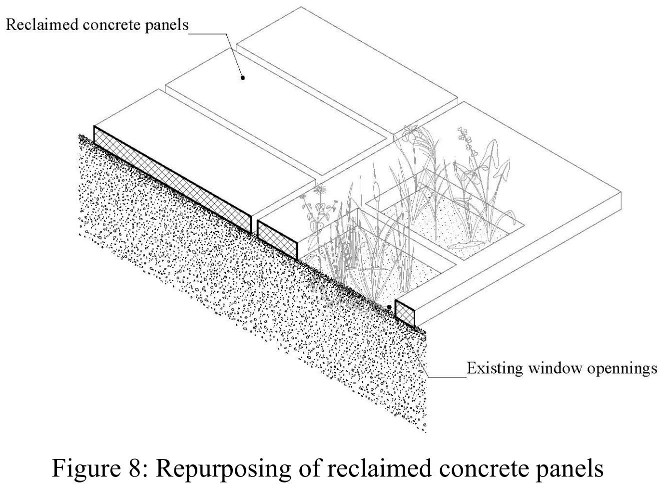


Figure 8: Repurposing of reclaimed concrete panels

It is important to acknowledge that the implementation of the design-by-availability approach in the Pokfield Campus Development project would not be without challenges. The availability of suitable salvaged components, the need for additional processing or treatment, and the coordination between the deconstruction and construction phases are factors that would require careful consideration. Furthermore, while the use of steel joints facilitates easier deconstruction and reuse in the next life cycle, the production of steel itself is energy-intensive and contributes to carbon emissions. The specific environmental and economic benefits of this approach would require more comprehensive data and analysis, which is currently not available.

Despite these limitations, the hypothetical application of the design-by-availability approach to the Pokfield Campus Development project demonstrates the potential for creating innovative, sustainable, and contextually relevant designs that align with the principles of the design-in-waste framework. As more projects adopt this approach and data becomes available, the quantitative benefits can be better understood and optimized.

6. Discussion and conclusion

The design-in-waste framework, as demonstrated through the HKU residence building case study, offers a promising approach to promoting a circular economy in the construction industry. By incorporating the principles of reusable components estimation, design for disassembly, and design by availability, this framework provides a systematic way to maximize the reuse potential of salvaged building components and reduce waste in the construction process.

However, the application of the framework is not without limitations, such as the lack of on-site inspection, logistical challenges related to storage and quality control, and the time gap between deconstruction and new projects. Addressing these limitations will require further research and development, including the integration of advanced technologies like robotics, computer vision, scan-to-BIM, and AI-assisted design generation.

The successful implementation of the design-in-waste framework also relies on the support and collaboration of various stakeholders, particularly the government. Through policy incentives, public procurement, and awareness-raising initiatives, governments can play a crucial role in mainstreaming the reuse of building components and accelerating the transition towards a circular economy in the construction industry.

As more exemplary projects demonstrate the benefits of the design-in-waste approach, it is hoped that the reuse of building components will become common practice, contributing to a more sustainable and resilient built environment.

Acknowledgements

The authors would like to express their sincere gratitude to the Environmental Protection Department (EPD) of Hong Kong for providing access to the Construction Waste Disposal Charging Scheme (CWDCS) data, which was crucial for analyzing the waste generation and disposal practices in the case study.

References

[1] Y. Wu, K. W. Chau, W. Lu, L. Shen, C. Shuai, and J. Chen, "Decoupling relationship between economic output and carbon emission in the Chinese construction industry," *Environmental Impact Assessment Review*, vol. 71, pp. 60-69, 2018.

[2] A. Akhtar and A. K. Sarmah, "Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective," *Journal of Cleaner Production*, vol. 186, pp. 262-281, 2018.

[3] Y. Zhang, S. Hu, F. Guo, A. Mastrucci, S. Zhang, Z. Yang, and D. Yan, "Assessing the potential of decarbonizing China's building construction by 2060 and synergy with industry sector," *Journal of Cleaner Production*, vol. 359, p. 132086, 2022.

[4] W. Lu, L. Yuan, and F. Xue, "Investigating the bulk density of construction waste: A big data-driven approach," *Resources, Conservation and Recycling*, vol. 169, p. 105480, 2021.

[5] W. Lu and V. W. Tam, "Construction waste management policies and their effectiveness in Hong Kong: A longitudinal review," *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 214-223, 2013.

[6] M. van den Berg, L. Hulsbeek, and H. Voordijk, "Decision-support for selecting demolition waste management strategies," *Buildings and Cities*, vol. 4, no. 1, pp. 883-901, 2023.

[7] J. Xiao, Y. Xiao, Y. Liu, and T. Ding, "Carbon emission analyses of concretes made with recycled materials considering CO2 uptake through carbonation absorption," *Structural Concrete*, vol. 22, pp. E58-E73, 2021.

[8] E. MacArthur, "Towards the circular economy," *Journal of Industrial Ecology*, vol. 2, no. 1, pp. 23-44, 2013.

[9] S. Banihashemi, S. Meskin, M. Sheikhkhoshkar, S. R. Mohandes, A. Hajirasouli, and K. Lenguyen, "Circular economy in construction: The digital transformation perspective," *Cleaner Engineering and Technology*, p. 100715, 2023.

[10] V. Nicholson and A. Miatto, "Architects as catalysts of reuse in construction," *Nature Cities*, vol. 1, no. 3, pp. 179-181, 2024.

[11] T. Joensuu, H. Edelman, and A. Saari, "Circular economy practices in the built environment," *Journal of Cleaner Production*, vol. 276, p. 124215, 2020.

[12] N. Bouchard, Ed., *Waste Matters: Adaptive Reuse for Productive Landscapes*. Routledge, 2020.

[13] EPD, "Construction Waste Disposal Charging Scheme," Environmental Protection Department, Hong Kong. [Online]. Available: https://www.epd.gov.hk/epd/misc/cdm/scheme.htm. [Accessed: March 15, 2024].

[14] New Progress Construction Company Limited, "Demolition Plan for Proposed Capital Development Complex at the Pokfield Road Site," unpublished, December 10, 2020.

[15] E. Stricker, G. Brandi, A. Sonderegger, M. Angst, B. Buser, and M. Massmünster, *Bauteile wiederverwenden: ein Kompendium zum zirkulären Bauen*, Park Books, 2021.

[16] T. A. Napp et al., "Cement and steel — nine steps to net zero," *Nature*, vol. 603, pp. 574-577, Mar. 2022. [Online]. Available: https://doi.org/10.1038/d41586-022-00758-4

[17] "Recylinghaus – New European Bauhaus Prizes," New European Bauhaus, 2021. [Online]. Available: https://2021.prizes.new-european-bauhaus.eu/node/269277. [Accessed: March 14, 2024].