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建築循環度評估研究：材料循環度指標之
擴充發展及臺灣案例驗證

Building Circularity Assessment: Expanding the Material
Circularity Indicator with New Factors and Validation in a
Taiwanese Case Study

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with New Factors and Validation in a Taiwanese Case Study

本論文係 張芸翠 君 (D05521009) 在國立臺灣大學土木工程學系
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完成博士論文的這段旅程，對我不僅是學術的累積，更是自我探索與成長的歷程。在這裡，我要衷心感謝一路上給予我支持與鼓勵的每一位。

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本論文部分內容改寫自本人已發表之期刊論文：Chang, Y.T & Hsieh, S. H. (2025). 〈Development and application of an enhanced building circularity indicator: A pilot study in Taiwan〉，《Journal of Cleaner Production》，502, 145363。該期刊論文呈現本研究核心成果，於本論文進一步擴充指標應用分析，以深化對循環建築評估工具理解與實踐建議。

中文摘要



循環經濟的概念主張材料或產品的再利用與再生，是解決建築產業所面臨環境挑戰的關鍵方案。此概念如何協助建築部門邁向永續，已成為利害關係人關注的重要課題。Ellen MacArthur 基金會所提出的「材料循環指標」（Material Circularity Indicator, MCI）已被用於評估建築的循環性，但其應用仍不夠全面。本文回顧現有建築領域中關於 MCI 的文獻，並提出一套加強版評估架構——「建築循環性強化指標」（Enhanced Building Circularity Indicator, EBCI），以彌補其侷限性。EBCI 納入了許多常被忽略的要素，例如輕量化設計、回收程度、模組化程度，以及全生命週期的觀點。

本研究以台灣首個循環住宅專案——台糖循環聚落（Taisugar Circular Village, TCV）為案例進行實證測試。該案整合了循環建材、模組化設計及產品即服務（Product-as-a-Service）等循環經濟策略。結果顯示，EBCI 能有效評估從材料、產品、系統到建築層級的循環性，並凸顯回收程度、模組化與使用壽命延長對提升建築循環性的重要性。此外，研究發現不同的標準化因子（如質量與經濟價值）對評估結果有顯著影響；而納入整修次數（RTs）對評分的影響有限，顯示該因子對整體評估的增益不大。EBCI 提供了一套全面且具適應性的建築循環性評估方法，為政策制定者與產業利害關係人推動永續建築實踐提供寶貴的洞見。

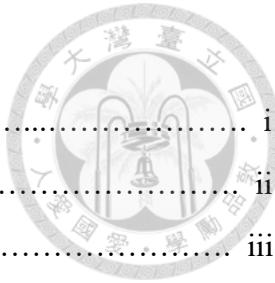
關鍵詞：循環經濟、評估方法、示範案例、案例研究、建築資訊模型、工程量清單

Abstract

The concept of circular economy, which promotes the reuse and regeneration of materials or products, is a key solution to the environmental challenges posed by the building industry. How this concept can facilitate the building sector's transition to sustainability has become a critical question for stakeholders. The Ellen MacArthur Foundation's "Material Circularity Indicator" (MCI) has been adopted to evaluate building circularity, but its application lacks comprehensiveness. This study reviews existing literature on MCI for buildings and proposes an enhanced framework, the "Enhanced Building Circularity Indicator (EBCI)," to address these limitations. The EBCI incorporates often overlooked factors such as lightweight design, recycling levels, modularity, and a whole lifecycle perspective. The framework is tested through Taiwan's Taisugar Circular Village (TCV), the country's first circular housing project, which integrates circular economy strategies, including circular materials, modular design, and Product-as-a-Service business models. Results show that the EBCI effectively assesses building circularity across material, product, system, and building levels, highlighting the importance of recycling levels, modularity, and lifespan extension in improving circularity. The study also discovers that different normalization factors (mass vs. economic value) significantly impact the results. Including renovation times (RTs) in the assessment leads to minimal differences in circularity scores, suggesting limited additional value for this factor. The EBCI provides a comprehensive and adaptable approach to assessing building circularity, offering valuable insights for policymakers and industry stakeholders seeking to promote sustainable building practices.

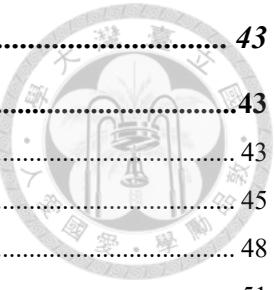
Keywords: Circular Economy, Assessment Method, Pilot Project, Case Study, Building Information Modeling, Bill of Quantities

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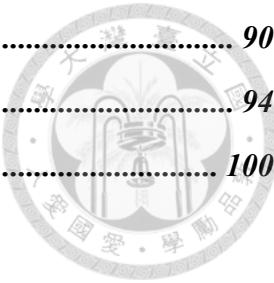


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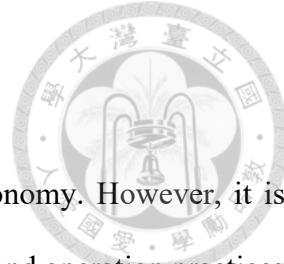
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1. Introduction



The building industry is a fundamental component of the global economy. However, it is problematic for the world environment, as its modern design, construction, and operation practices lead to the vast consumption of raw materials and the rapid generation of solid waste, causing serious environmental problems. According to the Ellen MacArthur Foundation (EMF) and Arup's publication on the circular built environment (Acharya et al., 2018), the construction industry currently accounts for 13% of the global economy's GDP. It employs approximately 7% of the world's working-age population (Barbosa et al., 2017). Moreover, the United Nations has predicted that over the next three decades, more than two-thirds of the world's population will reside in urban areas. This substantial urban expansion is expected to double the size of the built environment, placing a heightened strain on essential urban systems, including water, energy, and waste networks (UNDESA, 2018). Despite advancements in energy efficiency and urban livability, the current built environment still adheres to a linear production and consumption model characterized by the extraction, utilization, and disposal of materials as waste. This approach has made the built environment one of the largest consumers of resources and raw materials globally and a significant contributor to waste generation and carbon emissions (Acharya et al., 2018). For instance, in the European Union, more than 30-50% of the total material use is devoted to housing. And construction and demolition activities alone account for 25 to 30% of total waste generated (European Commission, 2016). Moreover, the production of cement and steel for construction contributes to nearly 10% of global CO₂ emissions (Levi et al., 2020).

Like other industries, the building industry's serious environmental problems worldwide are caused by its linear economic model. They can be fundamentally solved by transitioning to a

circular model, which refers to an industrial system designed to be restorative or regenerative (EMF, 2013). In another report published by the EMF and Material Economics on the impact of the circular economy (CE) on climate (Gueye & Jeffries, 2019), it was found that adopting a circular economy approach in the built environment could potentially lead to a 38% reduction in global carbon emissions from building materials by 2050. This reduction would be achieved through a decrease in demand for steel, aluminum, cement, and plastic materials. Furthermore, by adopting circular economy principles in the built environment—a sector known for its high growth and waste—there is a significant opportunity to create more value. This would lead to an improved return on investment for investors and construction clients while also contributing to achieving carbon emissions targets (Gueye & Jeffries, 2019).

Although the idea of a CE has received considerable attention from stakeholders in the global building sector, the industry faces greater challenges and barriers to adopting these principles compared to other sectors (Adams et al., 2017). One key reason is that buildings are often constructed as unique, individual projects, which increases their complexity; every material used has its own life cycle and interacts dynamically with others across both space and time, involving numerous stakeholders throughout the project (Adams et al., 2017). Much of the existing research on CE practices has focused on short-lived manufactured products, often overlooking the unique complexities present in buildings (Pomponi & Moncaster, 2017). When viewed systemically, buildings represent a Meso-level entity—situated between Macro-level urban areas and Micro-level building components—yet analysis at the building level as an independent entity remains insufficient (Pomponi & Moncaster, 2017). Additionally, the lack of appropriate methods and tools for evaluating material circularity at the building level makes it difficult for the industry to fully identify and address the true challenges and opportunities of CE adoption (Charef & Emmitt, 2021).

A range of well-established methodologies, such as life cycle assessment (LCA) and material flow analysis (MFA), are commonly used in sustainability research within the built environment and can be further adapted to support circular economy studies (Pomponi & Moncaster, 2017). In 2015, the Ellen MacArthur Foundation (EMF) and Granta Design introduced the Material Circularity Indicator (MCI), a method based on MFA designed to evaluate the circularity of products (EMF & Granta Design, 2015). This indicator has since been adopted by various organizations and academic groups in the building sector to assess building circularity (Verberne, 2016; Madaster, 2018). However, buildings differ significantly from the short-lived industrial products for which the MCI was originally developed, as they comprise numerous materials and products with varying lifespans. While many studies have applied the MCI to analyze their building case studies (Heisel & Rau-Oberhuber, 2020; Cottafava & Ritzen, 2021), there remains a notable gap in comprehensive discussions on how the MCI might be tailored or enhanced to more accurately measure circularity in buildings (Khadim et al., 2022).

Given Taiwan's status as a densely populated island nation with limited natural resources, the country faces significant demands for construction within its built environment, making the reuse and recycling of building materials and components essential for environmental sustainability (Chang & Hsieh, 2019). Consequently, the circular economy concept is particularly pertinent to advancing sustainability in Taiwan's building industry (Chang & Hsieh, 2019). Motivated by global movements toward circular economy adoption, various public sector entities in Taiwan have begun incorporating these principles into their building projects (Tserng et al., 2021). However, the effectiveness of these circular strategies has yet to be thoroughly assessed, highlighting the need for a robust evaluation framework to measure building circularity and support the transition to a more sustainable built environment in Taiwan (Tserng et al., 2021).

Research Aim and Questions

This research aims to address the methodological gap in evaluating building circularity by developing an enhanced assessment framework tailored to the building scale. The specific research questions include:

- (1) What are the limitations of existing MCI-based methods when applied to building circularity assessment?
- (2) How can a more comprehensive and context-sensitive circularity indicator be developed to capture key CE aspects at multiple levels (material, product, system, and building)?
- (3) How do different normalization factors (mass vs. economic value) influence circularity evaluation outcomes?



Research Scope and Contribution

To address these questions, this study proposes an Enhanced Building Circularity Indicator (EBCI) that integrates twelve key factors, including elements from the original MCI, existing Building Circularity Indicators (BCIs), and newly introduced factors such as disassembly potential, modularity, recycling level, and lightweight design. The EBCI is applied to a pilot project—Taisugar Circular Village, Taiwan's first circular housing project—using both mass and price as normalization bases to compare results. Through this pilot assessment, the study offers insights into how circular practices can be more effectively quantified. The proposed framework not only supports design and policy decision-making but also contributes to advancing CE implementation in Taiwan's building sector and beyond.

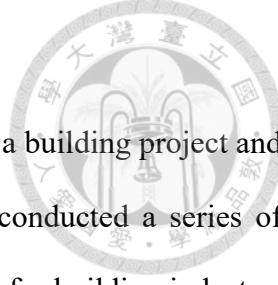
Structure of the Thesis

The remainder of this thesis is structured as follows:

- **Section 2** reviews the existing literature on CE in the building industry, assessment tools, and MCI-based indicators.
- **Section 3** details the development of the EBCI framework and the case study methodology.
- **Section 4** presents the results of the EBCI application across the four building systems.
- **Section 5** discusses the findings and implications for design, evaluation, and policy.
- **Section 6** concludes with a summary and recommendations for future research.



1. Literature Review



To understand the key strategies to implement the circular economy in a building project and existing assessment methods to measure building circularity, this study conducted a series of literature reviews covering the following three topics: (1) circular economy for building industry, (2) existing assessment methods for building circularity, and (3) MCI framework and MCI based building circularity indicators.

1.1 Circular Economy for the Building Industry

A circular economy (CE) is a resource production and consumption model in which materials and products are shared, leased, reused, repaired, refurbished, and recycled for as long as possible (EMF, 2013). Unlike the traditional linear economy, which follows a 'take-make-waste' pattern, a Circular Economy (CE) seeks to create a closed-loop system where resources are continually circulated by implementing three core principles: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems (see Figure 1). It has garnered significant attention in academia, business, and government in the past decade due to its potential to minimize carbon emissions, reduce raw material consumption, create new market opportunities, and enhance the sustainability of consumption (Tunn et al., 2019).

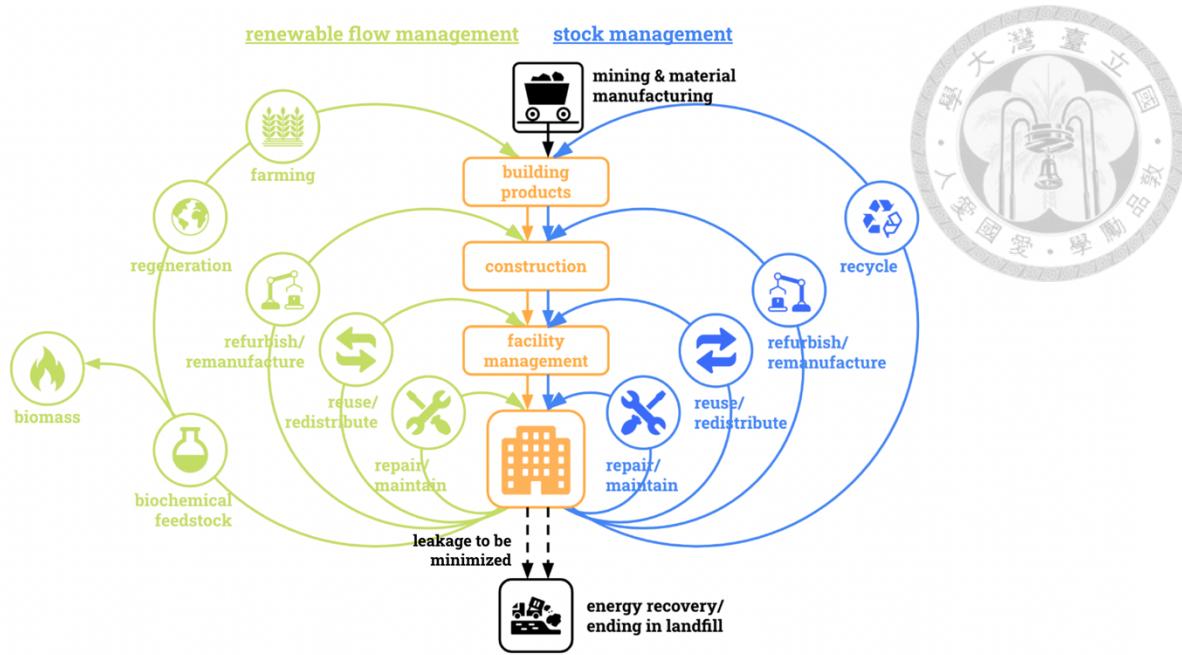


Figure 1. Circular Economy Principles in Building Value Chain (adopted from EMF, 2013)

Wasteful and unsustainable practices characterize the modern building industry. Despite consuming a significant portion of materials and resources, only a small fraction is currently reused, recycled, or regenerated. This results in a depletion of precious materials and resources while waste generation continues to increase (Cheshire, 2016). There is an urgent need for the building industry to transition from a linear economic model to a circular one to address these challenges. Recognizing the urgency of the situation, many public and private sectors worldwide have prioritized the implementation of CE principles in the building industry. For instance, the Dutch government has highlighted the building industry in its government-wide program for a CE (Government of the Netherlands, 2016). The "Building as Material Banks (BAMB)" project, a cross-national European research initiative, aimed to facilitate a systemic shift in the building sector by exploring and developing circular solutions (Debacker & Manshoven, 2016).

Adams et al. (2017) have identified the key CE aspects across a building's life cycle stages

(see Figure 2), which serves as a good knowledge base for understanding CE in building projects. In the meantime, Arup adopted the ReSOLVE model proposed by EMF to identify opportunities for the circular economy (CE) in the built environment (Arup, 2015). In their report, they listed seven different layers in the built environment, each with a distinct lifespan and function, following Stuart Brand's Shearing Layers (Brand, 1994), and highlighted that different strategies should be adopted accordingly. In the ReSOLVE model, several new business models for CE (e.g., Product-as-a-Service) are acknowledged. Furthermore, some researchers used the common R framework to identify CE strategies for building projects. For instance, Tseng et al. (2020) employed the 5R framework to examine the circular economy (CE)- related practices of five pilot circular building projects from Taiwan and the Netherlands.

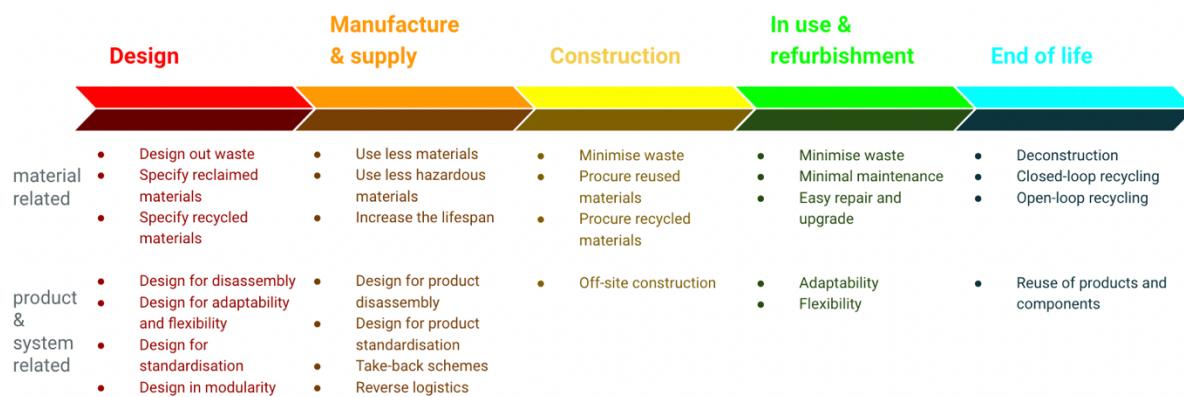


Figure 2. Circular Economy Aspects Across Building Lifecycle (adopted from Adams et al., 2017)

All these studies provide valuable insights into how to design, construct, operate, and deconstruct buildings for a CE. Nevertheless, which practices or strategies are more effective than others is an important question to be answered. The need to create a quantitative tool to evaluate the circularity of a building is vital for project stakeholders to make informed decisions and for policymakers to propose incentives and regulations accordingly. How this tool can accommodate all these key CE-related practices and strategies requires further exploration and investigation.

1.2 Assessing Building Circularity

1.2.1 The Features of the Circular Indicators



Circularity can be assessed by “Circular Indicators” (EMF & Granta Design, 2015). These indicators should be “quantitative or qualitative factors or variables that provide a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor” (OECD, 2014). They can offer a standardized language that simplifies the exchange and comprehension of information, facilitating the transition toward a circular economy. Additionally, they can assist policymakers and practitioners in establishing targets by quantifying the effectiveness of different strategies (Saidani et al., 2019). To ensure accuracy and comprehensiveness, these indicators should be detailed and encompass sufficient Key Performance Indicators (KPIs) that effectively capture the major aspects and accurately reflect the level of circularity achieved (Corona et al., 2019). Meanwhile, to maximize usability and avoid unnecessary complexity, these indicators should be user-friendly and noncomplicated. Excessive complexity could limit their application and create additional demands for advanced skills and sophisticated data (Arulnathan et al., 2020). Therefore, balancing the level of input details and the complexity of calculations is the primary challenge regarding these indicators (Zhai, 2020).

Indicators are categorized into different scales of measurement, including nano (product), micro (company), meso (industrial symbiosis), and macro (city, region) (De Oliveira et al., 2021). Buildings and materials can be classified within the hierarchy of indicators at the nano- and micro-levels (Zhai, 2020). In addition, various terms, including index (Esa et al., 2017), meter (Prins & Geraedts, 2015), scale (Nuñez-Cacho et al., 2018), and framework (Kubbinga et al., 2018), are

used by different authors to refer to similar concepts. However, all these variations refer to the same phenomenon: evaluating progress toward a specific target (De Oliveira et al., 2021). Therefore, for the sake of uniformity, following the work of Khadim et al. (2022), only the term “indicator” is used, and the micro-level (building) is the focus of this study.

Numerous circular indicators for different industries and products can be found in the literature. For example, Saidani et al. (2019) analyzed 55 indicators developed by scholars, governmental agencies, and consulting companies across different sectors. These indicators varied in terms of sophistication, scope, and potential usage. Their conclusion emphasized the crucial role of these indicators in informing policymakers and industry experts. They emphasized the need to further develop existing indicators, recognizing it as an inevitable step to enhance stakeholders' confidence. Generic indicators can provide a rough assessment of the circular performance of a proposed venture. Nevertheless, while less universally applicable, sector- or product-specific indicators can offer greater accuracy and specificity, thereby instilling confidence in their usage among stakeholders (Verberne, 2016). At present, the development and validation of building-specific indicators are relatively limited (Khadim et al., 2022).

Although the literature on implementing a circular economy in the building industry has grown fast in recent years, its practical application remains limited due to various social and technical barriers, including a lack of public awareness, insufficient technological innovations, and the absence of useful assessment methodologies (Charef & Emmitt, 2021). A recent review by Munaro et al. (2020) also highlighted the fragmented nature of circular economy research within the building industry, with a primary focus on material reuse and waste reduction (39%), while research on tools and assessments to support circular buildings accounts for only 17%. More research is needed to incorporate a comprehensive decision-making system into project planning,

considering various factors such as life cycle assessment (LCA), material flow analysis (MFA), material passports, and the potential for end-of-life reuse (Munaro et al., 2020). Numerous government bodies, such as the European Commission (EC), also emphasize the importance of developing practical building assessment methodologies (Dodd et al., 2021). In addition, the recently published ISO 20887 standards resemble the significance of robust assessment in evaluating and promoting circular economy practices among buildings and civil engineering works (ISO, 2020).

Although research on the development of building assessment schemes is greatly needed, it is a challenging task compared to other industry products. Rahla et al. (2019) have listed several obstacles and barriers to measuring building circularity. They highlighted the building's complexity from a construction engineering perspective and the difficulty in data collection and management. To address these two challenges, they emphasized the decomposition of different building components based on their expected lifespan (Brand, 1994) and the use of the Building Information Model (BIM) for the endorsement needed at the building level. In addition, they highlighted the plethora of CE definitions, confusion between assessing sustainability and circularity, obsolete and arbitrary indicators, and ambiguity in weighting and scoring as other crucial barriers to overcome when establishing a useful assessment scheme for building circularity.

1.2.2 The Existing Building Circularity Indicators (BCIs)

According to Khadim et al. (2022), 24 distinct building circularity indicators (BCIs) and 35 different versions were identified from the 51 selected articles and reports for assessing nano- and micro-level building circularity. There has been a significant surge in related publications since 2015, with Europe leading the way, while North American and Asian countries have lagged in this trend. In addition to academic societies, government sectors, and consulting companies,

several BCIs have also been developed by these entities.

Khadim et al. (2022) have also conducted a series of content analyses of these indicators based on their scale of application, calculation method, and base framework. Their results show that the applicability of these BCIs varies depending on the analysis stage (existing or new buildings), building type (residential, commercial, or historical), and the scale of measurement (material, product, or building). The majority (23) provide quantitative measurements of building circularity, while a smaller number (9) offer semi-quantitative assessments. Only three indicators utilize qualitative methods. Furthermore, most indicators (25) were developed based on existing tools, e.g., MCI, Design for Disassembly (DfD), Design for Adaptability (DfA), LCA, LCCA, BREEAM, and LEVEL(s). Only a subset of authors (10) has developed their frameworks by defining various circular key performance indicators (KPIs), employing various research methodologies. The variation in preference is visually depicted in Figure 3. As shown in Figure 3, EMF's MCI has gained significant adoption among academics and industry consultants in the construction field.

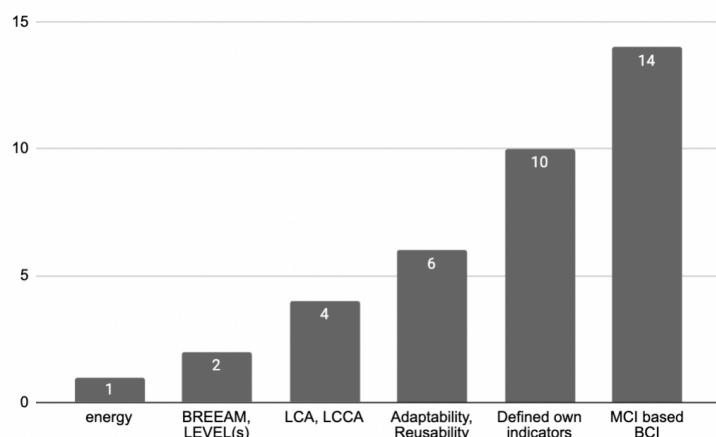


Figure 3. The base framework of identified building circularity indicators (adopted from Khadim et al., 2022)

In addition to analyzing existing BCIs, Khadim et al. (2022) identified five main research gaps and proposed future directions for the development of BCIs. First, to ensure comprehensive coverage, future frameworks should encompass all major aspects of circularity. Efforts should be made to conduct research that systematically categorizes and prioritizes the extensive KPIs from academia, contractors, policymakers, clients, and government agencies. Second, the progress made in different indicators has been fragmented and scattered. It is crucial for future advancements to be uniform and aligned with previous research to promote consistency and coherence. Third, several authors have highlighted the challenge of achieving a satisfactory level of detail, which poses obstacles to conducting comprehensive circular evaluations (van Schaik, 2019; Cottafava & Ritzen, 2021). As a result, there is a requirement to establish guidelines for conducting Building Materials (BOM) surveys and determining the appropriate level of detail to be included in the circular assessment of buildings. Fourth, there is a need for the development of open-source databases that house essential information, such as Bill of Materials (BOM), material properties, building codes, Embodied Carbon (EC), Embodied Energy (EE), and other relevant data. Integrating circularity into the Building Information Modeling (BIM) data model would be advantageous, allowing for a more streamlined and automated process. Fifth, quantitative indicators that have been analyzed normalize the scores using various environmental and economic (KPIs) such as mass (kg), EC, EE, and price. However, the suitability of using these KPIs as normalization factors is a subject of debate and requires additional investigation. It is recommended to thoroughly examine which specific KPIs accurately represent the value of materials, elements, and systems installed in a building.

1.3 MCI for Assessing Building Circularity



1.3.1 Material Circularity Indicator (MCI) Framework

The Material Circularity Indicator (MCI) tool was created through the collaborative Circular Indicators Project by the Ellen MacArthur Foundation and Granta Design, equipping businesses with a method to uncover and leverage the additional circular value present in their products and materials (EMF & Granta Design, 2015). By adopting the MCI tool, organizations are better able to manage risks linked to fluctuations in material prices and supply, thereby strengthening their circularity initiatives (EMF & Granta Design, 2015). The first version of the MCI methodology, launched in 2015, primarily focused on technical cycles and materials sourced from non-renewable resources. The most recent update in 2019 broadened the scope to include biological materials, allowing for a more comprehensive assessment of all material types (EMF & Granta Design, 2015).

The Material Circularity Indicator (MCI) evaluates how effectively a product reduces linear material flows and enhances restorative flows for its component materials. It also takes into account both the duration and intensity of the product's use compared to a typical industry product (EMF & Granta Design, 2015). The MCI calculation is based on three main product attributes: the mass of virgin raw materials used in production (V), the mass of waste that cannot be recovered (W), and a utility factor (X) that reflects how long and how intensively the product is used. By integrating these elements, the MCI offers a comprehensive measure of a product's circularity, addressing material inputs, waste output, and usage patterns over time. Figure 4 depicts the schematic of material flows, while Figure 5 summarizes the variables that influence the MCI and presents its principal formula.

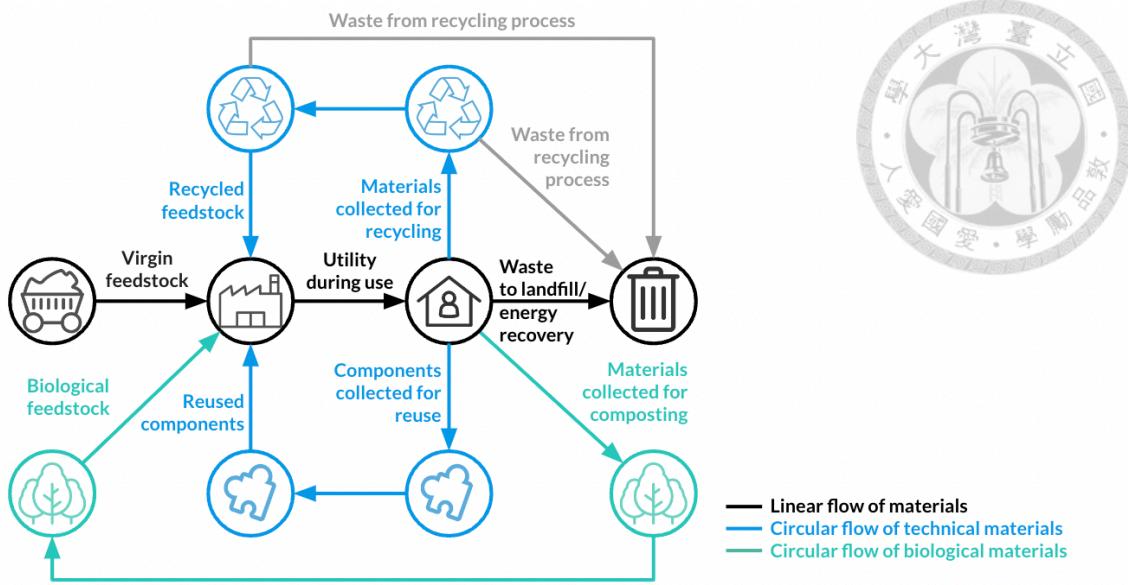


Figure 4. Diagrammatic representation of material flows in MCI methodology (adopted from EMF & Granta Design, 2019)

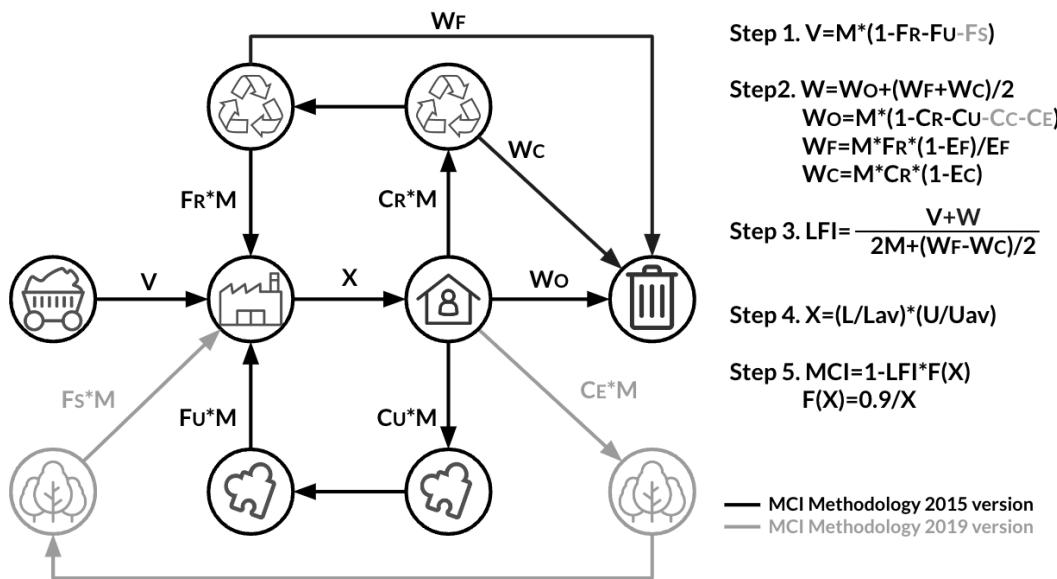


Figure 5. Key variables and calculation formula in MCI methodology (adopted from EMF & Granta Design, 2019)

According to EMF & Granta Design's definition (2015), a product that relies solely on virgin feedstock during manufacturing and is ultimately disposed of in a landfill at the end of its use phase can be classified as a fully "linear" product. Conversely, a product that contains no virgin

feedstock, is entirely collected for recycling or component reuse, and achieves a recycling efficiency of 100% can be considered a fully “circular” product. In reality, most products fall somewhere between these two extremes, and the MCI quantifies the degree of circularity within the range of 0 to 1. Additionally, the dashed lines in Figure 2 signify that the methodology does not mandate a closed-loop system. For instance, recycled feedstock does not necessarily have to come from the same product but can be sourced from the open market.

According to its updated methodology (EMF & Granta Design, 2019), MCI is calculated by following five key steps:

(1) Calculating Virgin Feedstock (V):

The following variables are considered to calculate the virgin feedstock for a product (V): F_R represents the fraction of feedstock derived from recycled sources, F_U is the fraction from reused sources, and F_S is the fraction of biological materials used from Sustained Production. Therefore, the mass of virgin material (V) can be calculated as $V=M(1-F_R-F_U-F_S)$, where M is the mass of the finished product.

(2) Calculating Unrecoverable Waste (W):

The overall amount of unrecoverable waste (W) is given by $W=W_O+(W_F+W_C)/2$, where W_O stands for the total amount of waste going to landfill or energy recovery, W_F indicates the waste generated to produce any recycled content used as feedstock, and W_C the quantity of waste generated in the recycling process.

The following variables are used to calculate the waste going to landfill or energy recovery (W_O): C_R represents the fraction of the mass collected for recycling, C_U is the fraction used for component reuse, C_C is the fraction comprising uncontaminated biological materials being composted, and C_E is the fraction comprising biological materials from Sustained Production used

for Energy Recovery. Therefore, the waste mass going to landfills or energy recovery (W_O) can be calculated as $W_O = M(1 - C_R - C_U - C_C - C_E)$.

Meanwhile, the waste created during the production of recycled content used as feedstock (W_F) can be measured as $W_F = M \cdot /_R (1 - E_F)/E_F$, where E_F represents the efficiency of the recycling process employed to produce the recycled feedstock. The waste generated in the recycling process (W_C) can be computed as $W_C = M \cdot C_R(1 - E_C)$, where E_C represents the efficiency of the recycling process used to recycle the product at the end of its use phase.

(3) Calculating Linear Flow Index (LFI):

The Linear Flow Index (LFI) quantifies the percentage of material that follows a linear flow, meaning it originates from virgin materials and ultimately becomes unrecoverable waste. The LFI is calculated by dividing the amount of material in linear flow by the total mass flow. The index ranges from 0 to 1, with 1 representing a fully linear flow and 0 indicating a fully restorative flow. The index is given by: $LFI = (V + W)/(2M + (W_F - W_C)/2)$.

(4) Calculating Utility (X):

The utility of a product (X) consists of two components: one that considers the duration of the product's use phase (lifetime) and another that considers the intensity of use (functional units). These two components are combined to form the utility as $X = (L/Lav)(U/Uav)$.

The length component (L/Lav) accounts for the impact of a product's lifetime (L) on the waste stream compared to the industry average lifetime (Lav). The component assumes that if a product's lifetime is doubled, the waste and virgin materials used per year by the linear flow of the product are halved. Meanwhile, the intensity of use component (U/Uav) captures the degree to which a product is utilized to its full capacity. This component provides insight into how efficiently the product is utilized during its lifespan.

(5) Calculating Material Circularity Indicator (MCI):

The Material Circularity Indicator (MCI) of a product is defined by considering the Linear Flow Index (LFI) of the product and a factor $F(X)$, which is determined based on the utility (X) of the product. By joining the LFI and the utility factor, the MCI provides a comprehensive measure of the product's circularity. The equation of MCI is $MCI=1-LFI\cdot F(X)$. The utility factor $F(X)$ is designed to penalize products with short lifetimes and poor utilization while rewarding those with longer lifetimes and better utilization. The function F is defined as $F(X)=a/x$, as a is set to 0.9.

1.3.2 MCI-Based Building Circularity Indicators (BCIs)

Khadim et al. (2022, 2023) report that seven distinct Building Circularity Indicators (BCIs) have been created by various European research institutions and consulting firms, all drawing from the Ellen MacArthur Foundation's Material Circularity Indicator (MCI) methodology and designed for application across different building types. Given the inherent complexity of buildings—which consist of numerous materials and products—the assessment of BCIs extends beyond the material level to include product, system, and entire building scales. The calculation frameworks and formulas for these six BCIs are systematically compared and detailed in Tables 1 and 2.

Verberne's 2016 thesis, published by Eindhoven University of Technology (TU/e), marked the first application of the Material Circularity Indicator (MCI) methodology developed by the Ellen MacArthur Foundation and Granta Design to assess building circularity. Building on this work, Van Vliet's 2018 thesis from TU/e adopted Verberne's framework and introduced enhancements specifically related to the assessment of building disassembly. In 2018, the Madaster Foundation, a Dutch non-profit organization, collaborated with the Ellen MacArthur Foundation to create their own Building Circularity Indicator (BCI) for integration into their digital

platform. Subsequently, researchers from the Netherlands and Italy, including Braakman et al. (2021) and Cottafava & Ritzen (2021), developed additional BCIs based on the MCI methodology and the prevailing BCI frameworks. Since 2016, Alba Concepts, a Dutch consulting firm, has also been developing its own BCI in partnership with TU/e, culminating in the launch of BCI Gebouw.

Table 1 and Figure 6 present a comparison of the calculation approaches used by various Building Circularity Indicators (BCIs) at the material level, highlighting key distinctions in how Virgin Feedstock (V), Unrecoverable Waste (W), and Utility (X) are determined. Initially, the early version of the Material Circularity Indicator (MCI) developed by EMF & Granta Design in 2015 focused exclusively on technical material flows, considering only select fractions of reuse and recycling during manufacturing and end-of-life phases (such as F_R , F_U , C_R , and C_U). This methodology was subsequently adopted by Verberne (2016), as well as by van Vliet (2018) and Cottafava & Ritzen (2021) in their respective studies. In later developments, Madaster (2018) and the updated EMF & Granta Design methodology (2019) acknowledged the significance of biological material flows, incorporating the proportion of biobased materials into their formulas (including factors like F_{RR} , F_S , C_C , and C_E). More recent frameworks by Braakman et al. (2021), BCI Gebouw & Alba Concepts (2022), and Khadim et al. (2023) have continued this direction by explicitly including biobased materials in their calculations (such as F_B , C_C , and C_B).

Secondly, to simplify calculations, many BCIs assume that the efficiency of recycling processes (E_F and E_C) is 100%, which means that the amount of unrecoverable waste (W) is equated solely to the waste sent to landfill or energy recovery (W_O) (Verberne, 2016; van Vliet, 2018; Cottafava & Ritzen, 2021; BCI Gebouw, 2022). This assumption, however, is often unrealistic and fails to capture a fundamental principle of the circular economy: that smaller material loops are preferable because they retain more value and require less energy, whereas

larger loops result in greater losses (Braakman et al., 2021). Furthermore, Khadim et al. (2023) expanded the scope of waste considered by including not only waste generated at the end of a building's life and during recycling, but also that produced during construction and maintenance phases. Finally, all BCIs to date have followed Verberne (2016) in considering only the length of use component (L/Lav), while assuming the intensity of use (U/Uav) to be 100%, resulting in the utility factor (X) being calculated as $X = (L/Lav)$.

Table 1. The comparison of calculation methods of different BCIs at the material level

EMF & Granta Design (2015)	Verberne (2016), van Vliet (2018)	Madaster (2018)	EMF & Granta Design (2019)
Step 1. $V=M(1-F_R-F_U)$	$V=M(1-NV_{RC})$	$V=M(1-F_R-F_U-F_{RR})$	$V=M(1-F_R-F_U-F_S)$
Step 2. $W=W_O+(W_F+W_C)/2$	$W=W_O$	$W=W_O+(W_F+W_C)/2$	$W=W_O+(W_F+W_C)/2$
$W_O=M(1-C_R-C_U)$	$W_O=M(1-F_{RU})$	$W_O=M(1-C_R-C_U)$	$W_O=M(1-C_R-C_U-C_C-C_E)$
$W_F=M \cdot F_R(1-E_F)/E_F$		$W_F=M \cdot F_R(1-E_F)/E_F$	$W_F=M \cdot F_R(1-E_F)/E_F$
$W_C=M \cdot C_R(1-E_C)$		$W_C=M \cdot C_R(1-E_C)$	$W_C=M \cdot C_R(1-E_C)$
Step 3. $LFI=(V+W)/[2M+(W_F-W_C)/2]$	$LFI=(V+W)/2M$	$LFI=(V+W)/[2M+(W_F-W_C)/2]$	$LFI=(V+W)/[2M+(W_F-W_C)/2]$
Step 4. $X=(L/L_{av})(U/U_{av})$	$X=(L/L_{av})$	$X=(L/L_{av})$	$X=(L/L_{av})(U/U_{av})$
Step 5. $MCI=1-LFI \cdot F(X)$	$MCI=1-LFI \cdot F(X)$	$MCI=1-LFI \cdot F(X)$	$MCI=1-LFI \cdot F(X)$
$F(X)=0.9/X$	$F(X)=0.9/X$	$F(X)=0.9/X$	$F(X)=0.9/X$

Table 1. (continual)

Braakman et al. (2021)	Cottafava & Ritzen (2021)	BCI Gebouw & Alba Concepts (2022)	Khadim et al. (2023)
Step 1. $V=M(1-F_R-F_U-F_B)$	$V=M(1-F_R-F_U)$	$V=M(1-F_R-F_U-F_B)$	$V=M(1-F_R-F_U-F_B)$
Step 2. $W=W_O+(W_F+W_C)/2$	$W=W_O$	$W=W_O$	$W=W_O+W_C+W_{el}+W_{rm}$
$W_O=M(1-C_R-C_U-C_C)$	$W_O=M(1-C_R-C_U)$	$W_O=M(1-C_R-C_U)$	$W_O=M(1-C_R-C_U-C_B)$
$W_F=M \cdot F_R(1-E_F)/E_F$			$W_C=M \cdot C_R(1-E_C)$
$W_C=M \cdot C_R(1-E_C)$			
Step 3. $LFI=(V+W)/[2M+(W_F-W_C)/2]$	$LFI=(V+W)/2M$	$LFI=(V+W)/2M$	$LFI=(V+W)/[2*(M+M_{el}+M_{rm})]$
Step 4. $X=(L/L_{av})$	$X=(L/L_{av})$	$X=(L/L_{av})$	$X=(L/L_{av})$
Step 5. $MCI=1-LFI \cdot F(X)$	$MCI=1-LFI \cdot F(X)$	$MCI=1-LFI \cdot F(X)$	$MCI=1-LFI \cdot F(X)$
$F(X)=0.9/X$	$F(X)=0.9/X$	$F(X)=0.9/X$	$F(X)=0.9/X$

*The bold font highlights the key differences between existing BCIs at the material level.

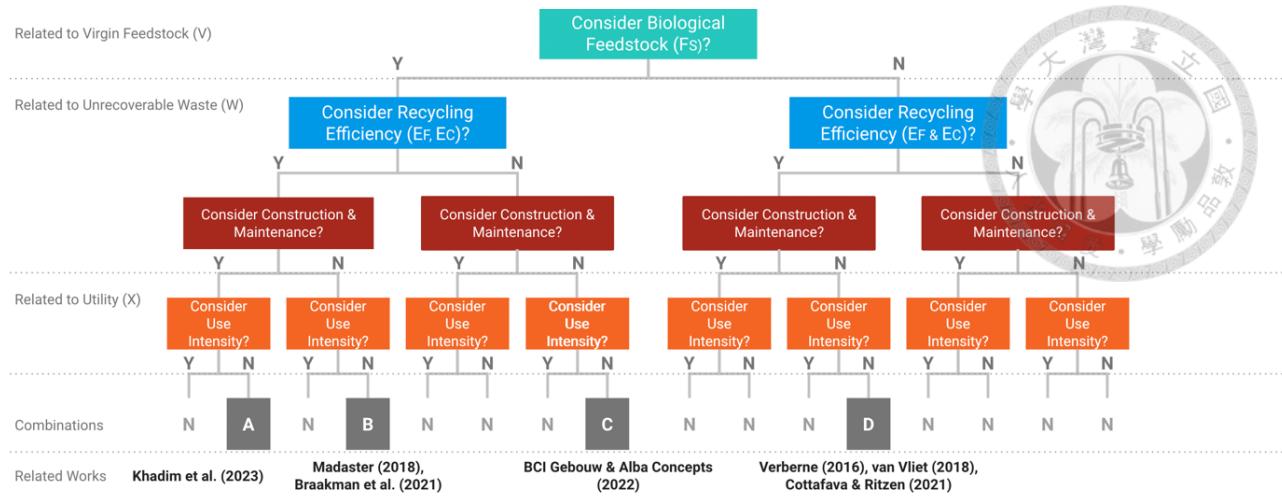


Figure 6. The comparison of calculation methods of different BCIs at the material level

Because buildings are complex structures made up of numerous materials and products, each connected in different ways and possessing distinct functions and lifespans, the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation (EMF) is insufficient for fully evaluating building circularity. To address this limitation, Verberne (2016) introduced a four-tiered assessment approach that examines circularity at the material, product, system, and whole-building levels (see Figure 7). In addition to assessing material circularity, Verberne (2016) incorporated a disassembly potential factor (F) at the product level to capture the diversity of construction methods and underscore the significance of disassembly for enabling reuse or recycling. For this purpose, he utilized 17 Disassembly Determining Factors (DDFs) identified by Durmisevic et al. (2006) to represent key elements of design for disassembly (DfD). Verberne (2016) also emphasized that the utility of building products should be evaluated differently depending on the building system they belong to, as their functions and expected lifespans can vary widely. To facilitate this differentiation, he adopted the 6S Layers framework proposed by Brand (1994), which categorizes building elements into site, structure, skin (exterior), space (interior), service (mechanical, electrical, and plumbing systems), and stuff (furniture). Lastly,

Verberne (2016) introduced the concept of a level of importance (L) to assess the relative significance of different systems in the context of building circularity, arguing—based on literature review, expert interviews, and panel input—that circularity is more relevant for products with shorter lifespans, and suggesting the use of fuzzy variables to represent this importance accordingly. Why is EMF's MCI insufficient for capturing the complexity of building circularity

How does Verberne's four-level assessment improve understanding of building reuse potential

What role do disassembly factors play in evaluating a building's circularity at the product level

How are different building systems' functions and lifespans considered in Verberne's framework

Why does Verberne emphasize the importance of system-level significance in assessing circularity.

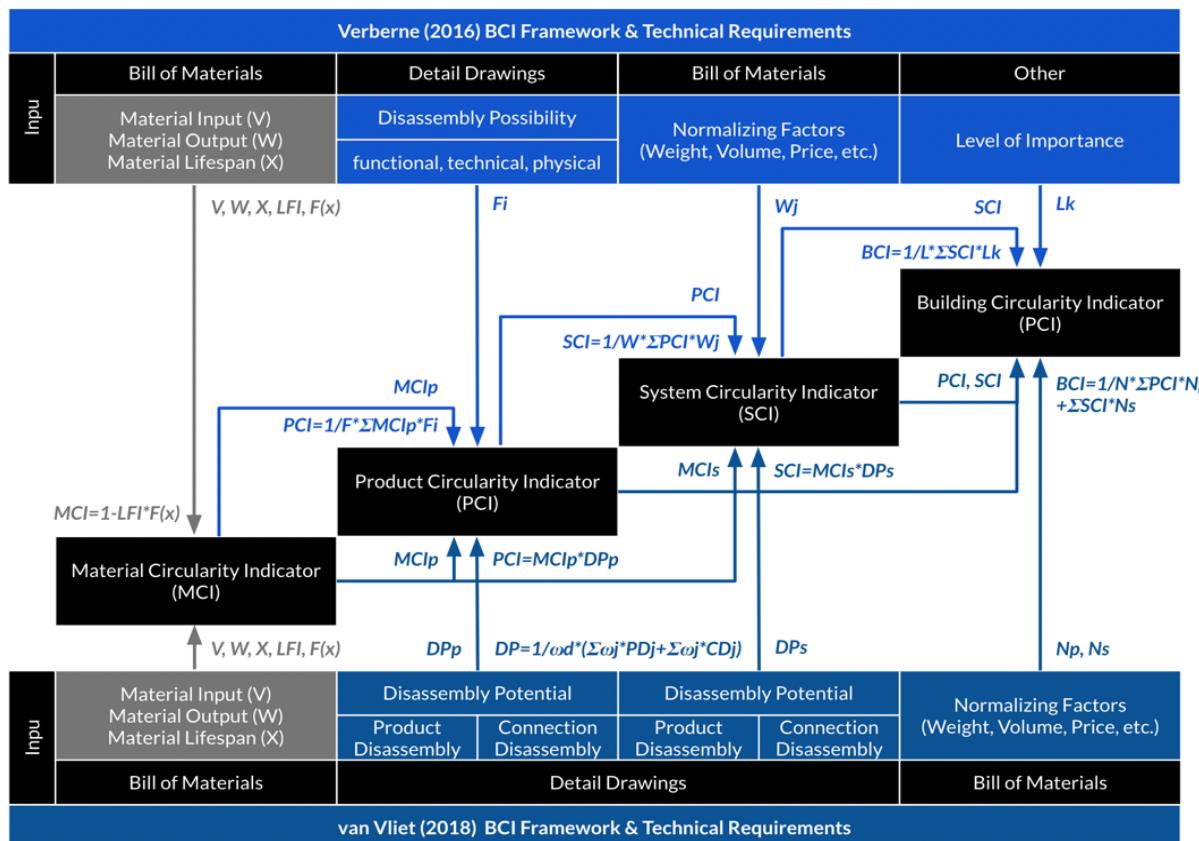


Figure 7. Key variables and calculation formula in Verberne (2016) and van Vliet (2018) BCI methodology (adopted from Verberne, 2016 and van Vliet, 2018)

Building on Verberne's (2016) work, van Vliet (2018) also adopted a four-level framework to evaluate building circularity (see Figure 6). As indicated by the focus of his thesis, van Vliet (2018) sought to enhance Verberne's Building Circularity Indicator (BCI) by revising the approach to building disassembly assessment. He pointed out that the process for selecting variables in Verberne's BCI lacked transparency, raising concerns about whether the most important factors were adequately included. Another limitation identified was that Verberne's BCI treated disassembly merely as an intermediate step between the Material Circularity Indicator (MCI) and the Product Circularity Indicator (PCI), whereas Durmisevic (2006) recommended a more holistic, systemic perspective. To address these issues, van Vliet (2018) utilized two rounds of the Fuzzy Delphi Method to determine the most significant disassembly factors and assign appropriate weights to them, ensuring these factors were considered in both the PCI and the System Circularity Indicator (SCI) assessments. Notably, van Vliet's framework omitted the consideration of the relative importance of different building systems in evaluating building circularity.

Building on Verberne's (2016) foundational work, several other MCI-based Building Circularity Indicators (BCIs) have adopted the four-level framework for evaluating building circularity. Braakman et al. (2021) and Cottafava & Ritzen (2021) utilized Verberne's (2016) calculation methods at the product, system, and building levels, whereas BCI Gebouw (2022) implemented the approach introduced by van Vliet (2018), as detailed in Table 2. A notable advancement in these models is the integration of an Environmental Cost Indicator (ECI) within the BCI calculation process. In contrast, Madaster (2018) streamlined the calculation by using mass as the sole normalization factor for deriving the Product, System, and Building Circularity Indicators (PCI, SCI, and BCI). Additionally, Khadim et al. (2023) shifted the consideration of disassembly from the product (element) level to the system level in their framework.

Table 2. The comparison of calculation methods of different BCIs at the product, system, and building level

Level	Verberne (2016)	van Vliet (2018)	Madaster (2018)
Product	$PCI = 1/Fd * \sum MCI * F$ F: Disassembly possibilities (functional, technical, physical)	$PCI = MCIP * DP_p$ DP: Disassembly potentials (product disassembly, connection disassembly)	$PCI = 1/M_p * \sum MCI * M$ M: Mass as the normalization factor
System	$SCI = 1/W_s * \sum PCI * W$ W: Weighting (weight, volume, price)	$SCI = MCIs * DP_s$ DP: Disassembly potentials (product disassembly, connection disassembly)	$SCI = 1/M_s * \sum PCI * M$ M: Mass as the normalization factor
Building	$BCI = 1/L_k * \sum SCI * L$ L: Level of importance	$BCI = 1/N_b * (\sum PCI_p * N_p + \sum SCI_s * N_s)$ N: Normalization factors (weight, volume, price)	$BCI = 1/M_b * \sum SCI * M$ M: Mass as the normalization factor

Table 2. (continual)

Level	Braakman et al. (2021) Cottafava & Ritzen (2021)	BCI Gebouw & Alba Concepts (2022)	Khadim et al. (2023)
Product	$PCI = 1/Fd * \sum MCI * F$ F: Disassembly possibilities	$PCI = \sqrt{MCIP * LI_p}$ LI: Detachability Index (connection type, accessibility, edge confinement, crossings)	$ECI = \sum MCII * MNi$ M: Mass as the normalization factor
System	$SCI = 1/W_s * \sum PCI * W$ W: Weighting (weight, volume, price)	$SCI = \sqrt{MCIE * LI_e}$ LI: Detachability Index (connection type, accessibility, edge confinement, crossings)	$SCI = \sum ECIi * EDII$ EDII: Element Disassembly Index (EDI)
Building	$BCI = 1/L_k * \sum SCI * L$ L: Level of importance	$BCI = 1/MKI * (\sum PCI_p * MKIp + \sum ECIE * MKIe)$ MKI: Environmental Cost Indicator	$BCI = 1/L_k * \sum SCI * L$ L: Level of importance

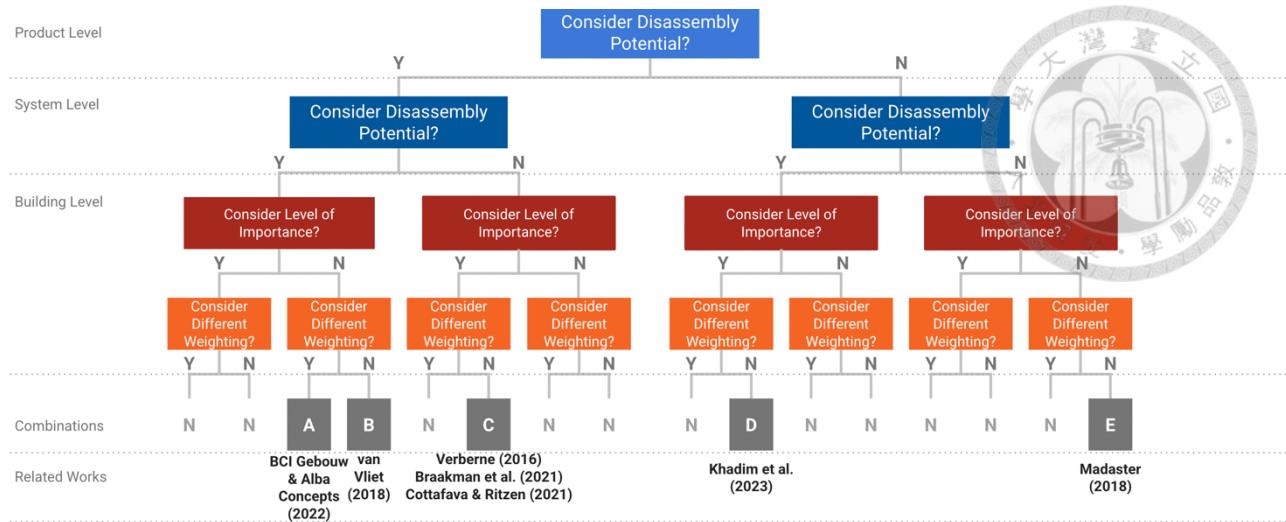
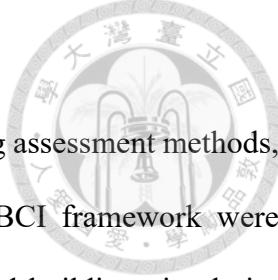


Figure 8. The comparison of calculation methods of different BCIs at the material level

The development of these seven Building Circularity Indicators (BCIs) has established a robust framework for applying the Material Circularity Indicator (MCI) in evaluating building circularity, effectively addressing the complexity of buildings through a four-level assessment structure and highlighting key factors related to product and system disassembly potential. However, several significant elements and strategies pertinent to circular buildings remain unaddressed, such as lightweight design, the degree of recycling (including upcycling, recycling, or downcycling), and modularity. Furthermore, the integration of innovative business models for the circular economy—such as Product-as-a-Service and the sharing economy—within an MCI-based BCI framework has yet to be explored. Finally, as previously noted, the influence of various normalization factors on BCI outcomes has not been systematically investigated.

2. Methods



After reviewing the key concepts of circular buildings, existing building assessment methods, and MCI-based BCIs, several research gaps for developing a suitable BCI framework were identified in the previous section. In this section, we propose an enhanced building circularity indicator (EBCI) to address the identified research gaps, and its effectiveness is tested through a pilot circular building project in Taiwan. This section also covers the key information about the selected study case, as well as the data collection and processing process for our case study.

2.1 Assessment Framework

Building on previous studies, a common four-level framework is adopted in this study to assess building circularity (see Figure 9). Twelve key factors are highlighted in our assessment framework. Four are derived from the MCI framework proposed by EMF and Granta Design (2019), four are adapted from existing BCIs, and four are newly proposed in this study. The following are additional explanations of these factors.

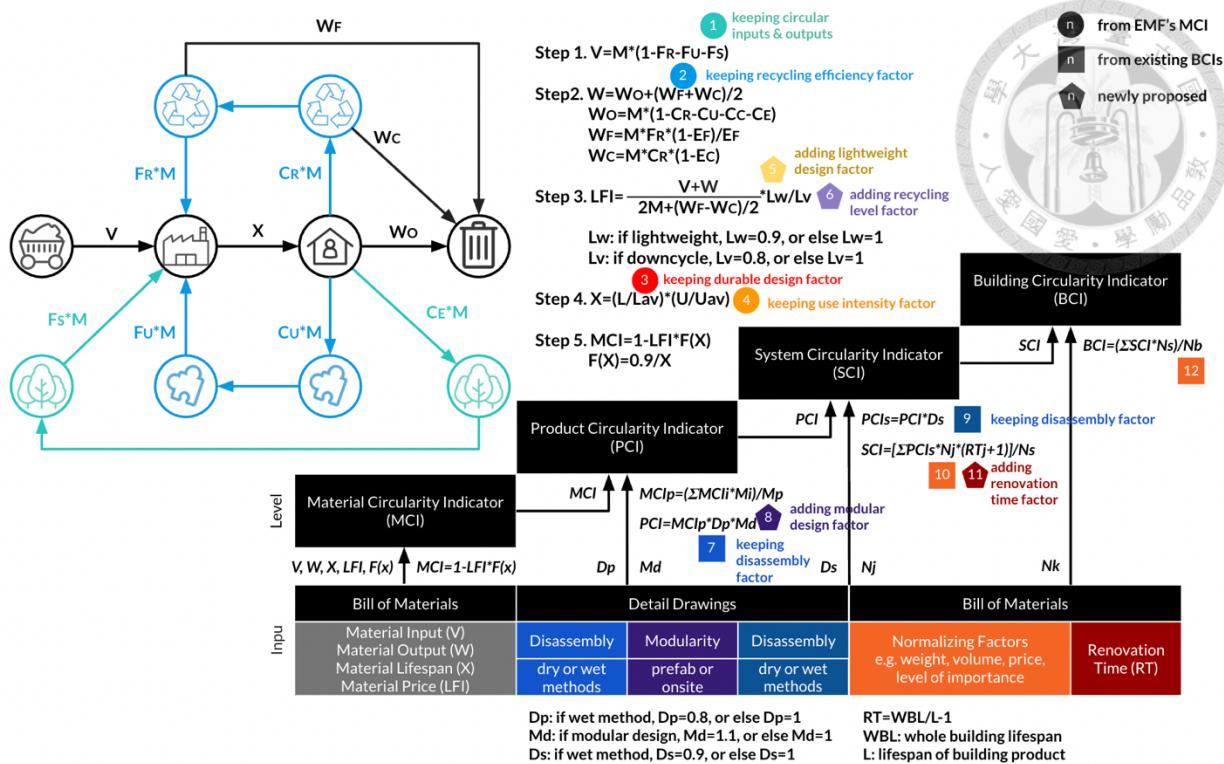


Figure 9. The proposed Enhanced Building Circularity Assessment (EBCI) framework in this study

2.1.1 Assessment at the Material Level

Figure 10 shows the material-level assessment framework of the proposed EBCI. More detailed information regarding the reasons for keeping existing factors from EMF's MCI and adding new factors to the proposed material circularity indicator (MCI) of EBCI are as follows.

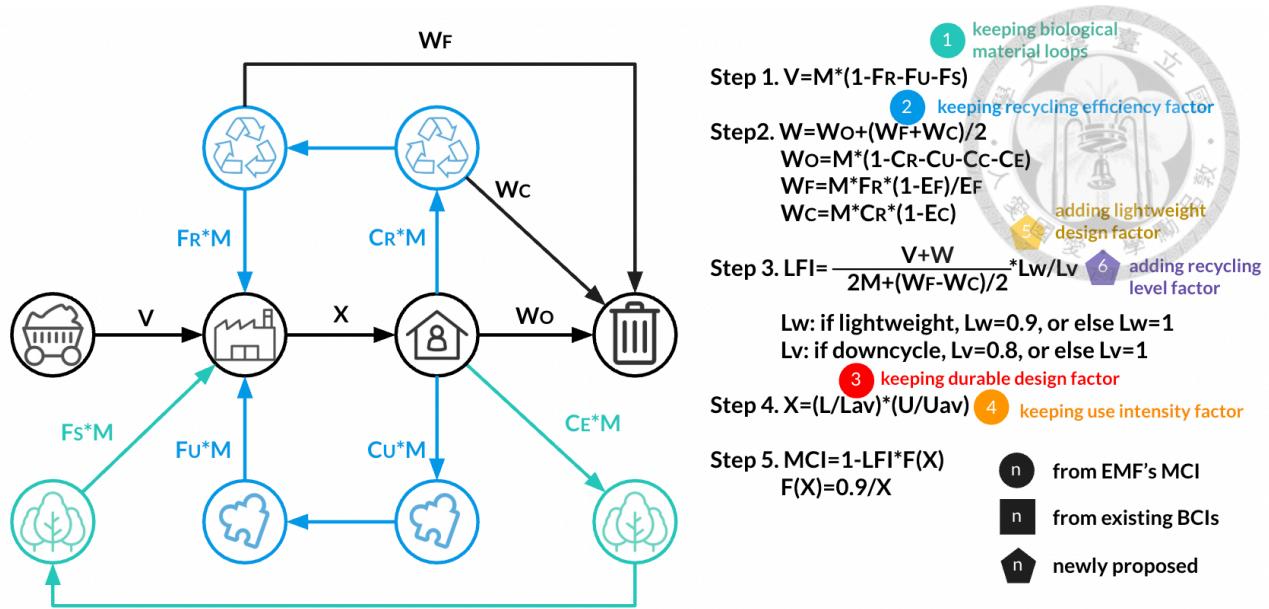


Figure 10. The proposed EBCI framework at the material level

Keeping factors from EMF's MCI

At the material level, four key factors proposed by EMF and Granta Design (2019) in their MCI framework are stressed and adopted in the proposed EBCI framework (see Figure 10), which are the considerations of biological material flow (F_s , C_c , C_e), the waste generated by the recycling process in technical material flow (W_F , W_c), the length (L/Lav) and the intensity of use component (U/Uav).

In previous studies, Brand's 6S Layers (1994) framework was widely used as a reference for determining which systems the building materials and products belong to and how to set the industry average lifespans (Lav) of different building systems. However, whether Brand's framework is sufficient and applicable for buildings with different purposes and located in different countries is rarely discussed. Besides the six building systems Brand proposed, the landscape (including both hard and soft elements) should be considered an individual system separate from the building site. Furthermore, falsework during construction should also be

considered as another building system that contributes to building circularity. In this study, the industry average lifespans (Lav) of different building systems proposed by the Low Carbon Building Alliance (LCBA) in Taiwan are used, which are determined by a series of surveys of Taiwan common building systems (LCBA, 2013), including structural, exterior, interior, MEP and landscape system.

Additionally, previous studies have neglected the intensity of the use component (U/Uav) when assessing building circularity. However, it can be useful for assessing different circular business models in building projects. For instance, product-as-a-service (PaaS) and product sharing are well-known models in the circular economy, which can increase the intensity of product use. In this study, this factor (U/Uav) is preserved to test how the assessment of circular business models can be incorporated into building circularity assessments.

Adding factors to EBCI's MCI

In addition to the four primary factors, this study introduces two innovative elements into the Material Circularity Indicator (MCI): lightweight design (Lw) and the level of recycling (Lv). Lightweight design has been identified as a crucial aspect of circular buildings in several studies (Tserng et al., 2021), yet it remains absent from current BCIs. To address this, a coefficient (Lw = 0.90) is applied in cases where a building product has a lower mass compared to standard alternatives. For example, a drywall partition system is much lighter than traditional brick or RC interior walls. The coefficient of 0.90 is used in this pilot project, reflecting findings from a preliminary survey indicating that many lightweight components are approximately 90% lighter than conventional options. Moving forward, this factor could be more precisely calculated as the ratio of the product's mass (M) to the mass of a typical equivalent product (Mav).

In many countries, the construction industry is considered circular, as it can utilize waste from other industries (e.g., incorporating blast furnace slag into cement). Furthermore, heavy construction waste can be easily reused (e.g., using waste concrete as aggregates for road construction). For instance, the Dutch government claimed that its construction industry is 88% circular because most construction waste is reused for new infrastructure projects (Government of the Netherlands, 2016). However, the goals of the circular economy are not merely to circulate the material flows but also to maintain the products' values. Hence, the assessment framework should distinguish between recycling levels (i.e., recycling, upcycling, and downcycling) to encourage the maintenance of product values. For instance, due to the requirement for structural capacity, wasted concrete can only be used as aggregate for non-structural components in many countries. This should be viewed as "downcycling" for assessing building circularity. In this study, a coefficient ($L_v = 0.80$) is applied to calculate LFI when the level of recycling in the end-of-life phase is downcycling. The coefficient is set at 0.80, as this study focuses on the difference brought about by varying levels of recycling, which should be noticeable in the assessment results, thereby fostering the construction industry's transition toward value retention.

Summary of MCI of EBCI

The same as EMF's MCI, five steps of calculation are required:

Step 1: Calculating Virgin Feedstock (V):

$$V = M * (1 - FR - FU - FS), \quad (1)$$

M: the mass of assessed building material

F_R : the fraction of feedstock derived from recycled sources

F_U : the fraction from reused sources

F_S : the fraction of biological materials used from sustained production

Step 2: Calculating Unrecoverable Waste (W):

$$W = W_O + \frac{W_F + W_C}{2} \quad (2)$$



W_O : the total amount of waste going to landfill or energy recovery

W_F : the waste generated to produce any recycled content used as feedstock

W_C : the waste generated in the recycling process

$$W_O = M * (1 - CR - CU - CC - CE) \quad (3)$$

C_R : the fraction of the mass collected for recycling

C_U : the fraction used for component reuse

C_C : the fraction comprising uncontaminated biological materials being composted

C_E : the fraction comprising biological materials used for Energy Recovery

$$W_F = M * FR * \frac{1 - EF}{EF} \quad (4)$$

E_F : the efficiency of the recycling process employed to produce the recycled feedstock

$$W_C = M * CR * (1 - EC) \quad (5)$$

E_C : the efficiency of the recycling process used to recycle the material at the end of its use phase

Step 3: Calculating Linear Flow Index (LFI):

$$LFI = \frac{V + W}{2M + \frac{WF - WC}{2}} * \frac{Lw}{Lv} \quad (6)$$

Lw : lightweight design factor. Suppose lightweight design takes place, $Lw=0.90$, or else $Lw=1.00$.

Lv : recycling level factor. Suppose downcycling takes place, $Lv = 0.80$, or else $Lv = 1.00$.

Step 4: Calculating Utility (X):

$$X = \left(\frac{L}{L_{av}} \right) \left(\frac{U}{U_{av}} \right) \quad (7)$$



L: the assessed product's lifetime

Lav: the industry average lifetime

U: the number of functional units achieved during the use of a product

Uav: the number of functional units achieved during the use of an industry-average product

Step 5: Calculating MCI:

$$MCI = 1 - LFI * F(X) \quad (8)$$

F(X): the utility factor

$$F(X) = \frac{a}{X}, \text{ where } a \text{ is set to 0.9} \quad (9)$$

2.1.2 Assessment at the Product Level

Figure 11 shows the product-leveled assessment framework of the proposed EBCI. More detailed information regarding the reasons for excluding existing BCIs and adding new factors to the proposed product circularity indicator (PCI) of EBCI is as follows.

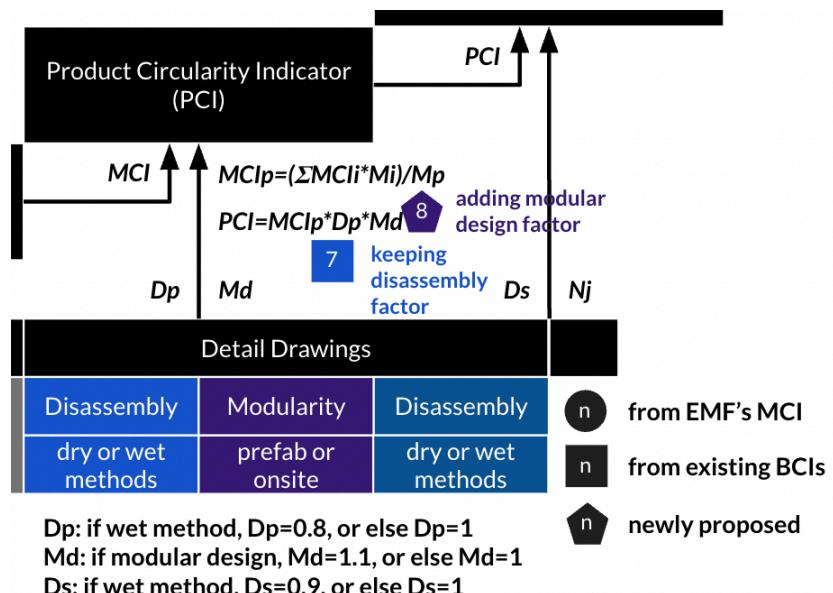


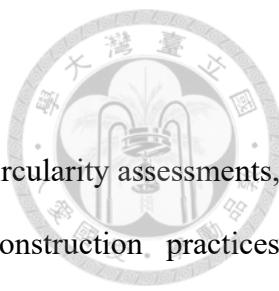
Figure 11. The proposed EBCI framework at the product level

Keeping factors from existing BCIs

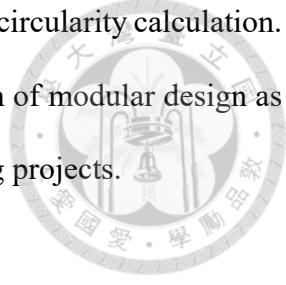
At the product level, the disassembly factor (D_p) is incorporated into circularity assessments, drawing from established BCIs. However, regional variations in construction practices significantly influence disassembly potential. In Taiwan, for example, seismic activity drives the widespread use of “wet methods”—construction techniques involving cement, such as cast-in-situ reinforced concrete components and brick walls—to enhance structural stability (see Figure 11). While effective for earthquake resistance, these methods reduce opportunities for future reuse or recycling of materials. To account for this, a deduction coefficient ($D_p = 0.80$) is applied when cement, adhesive, or welding is used in product assembly. This coefficient reflects the critical role of disassembly in enabling material recovery while acknowledging the challenges posed by Taiwan’s seismic design requirements, which make design-for-disassembly inherently more complex. The coefficient is maintained at 0.80 (rather than a lower value) to balance practicality with the need to incentivize disassembly-friendly practices in such contexts.

Adding factors to EBCI’s PCI

In addition to the disassembly factor (D_p), this study introduces a modularity factor (M_d) into the assessment of building circularity at the product level. Previous research has emphasized the significant role of modular design in promoting circularity within the built environment, as it can lower fabrication costs, reduce waste, and enhance the potential for product reuse (Adams et al., 2017). Despite its importance, modularity has not yet been incorporated into MCI-based BCI frameworks. To address this gap, this study adopts a straightforward approach: if a building product’s dimensions are predetermined during the design phase and the product is manufactured



off-site in a factory, an appreciation coefficient ($Md = 1.10$) is applied in the circularity calculation. This coefficient is set at 1.10 for the pilot project, reflecting the recognition of modular design as a valuable, though not critical, strategy for advancing circularity in building projects.



Summary of PCI of EBCI

Two steps of calculation are required for PCI:

Step 1: Calculating the MCI of a product (i.e., MCI_p):

$$MCI_p = \frac{\sum MCI_i * M_i}{M_p} \quad (10)$$

MCI_i : the MCI results of the different building materials in the assessed product

M_i : the mass of the different building materials in the assessed product

M_p : the mass of the assessed product

Step 2: Calculating PCI:

$$PCI = MCI_p * D_p * M_d \quad (11)$$

D_p : the disassembly factor. If cement, glue, or welding was used, $D_p=0.80$, or else $D_p=1.00$

M_d : the modularity factor. Suppose modular design takes place, $M_d=1.10$, or else $M_d=1.00$.

2.1.3 Assessment at the System & Building Level

Figure 12 shows the system and building-level assessment framework of the proposed EBCI.

More detailed information regarding the reasons for excluding existing BCIs and adding new factors to the proposed system circularity indicator (SCI) and building circularity indicator (BCI) of EBCI is as follows.

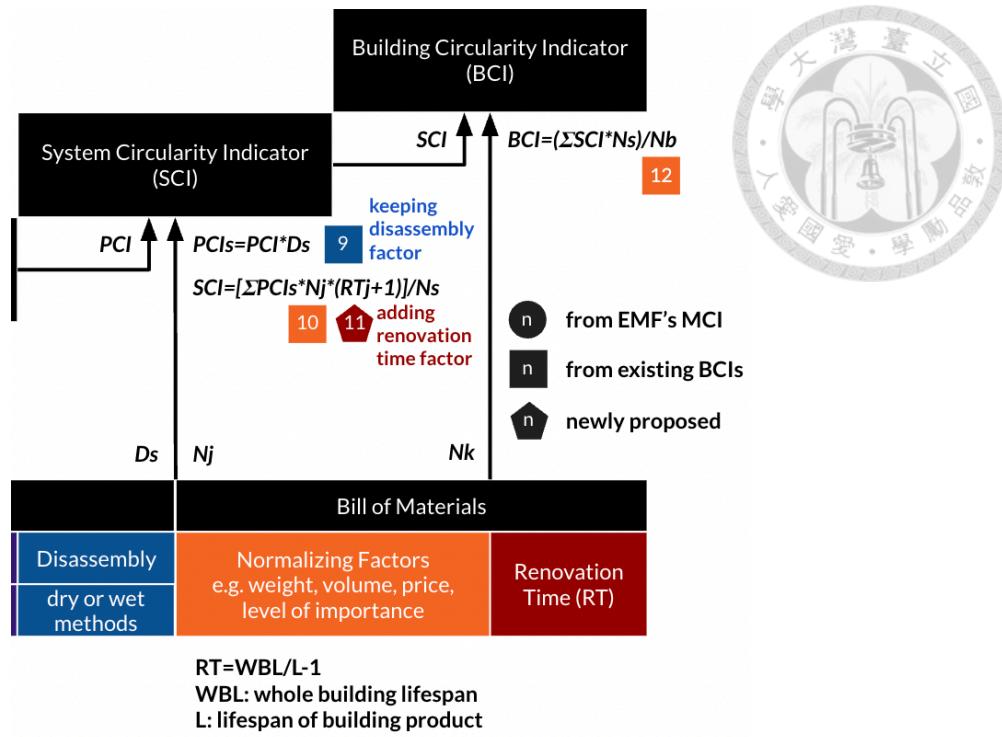


Figure 12. The proposed EBCI framework at the system and building level

Keeping factors from existing BCIs

The disassembly factor (D_s) is also integrated into circularity assessments at the system level. Mirroring the methodology applied at the product level, this study introduces a deduction coefficient ($D_s = 0.90$) when cement, adhesive, or welding is used to connect building products within a system (see Figure 12). This coefficient reflects the critical importance of system-level disassembly in facilitating the reuse of entire assemblies. While disassembly potential at both product and system levels is vital, D_s is assigned a higher coefficient than D_p (0.90 vs. 0.80) because system-level disassembly directly impacts larger assemblies, enabling broader reuse opportunities and more efficient material recovery. This prioritization emphasizes that system-level design choices have a greater influence on circular outcomes than individual product-level decisions.

Current research most frequently employs mass as the normalization factor (N) when calculating building circularity at various levels. This approach, however, tends to give disproportionate weight to the structural system, as its mass typically constitutes the largest portion of a building's total mass, thereby exerting a dominant influence on the final BCI (Christian et al., 2021). In contrast, building systems that may have higher value but lower mass—such as mechanical, electrical, and plumbing (MEP) systems—contribute minimally to the overall result. Additionally, the effects of using different normalization factors in circularity assessments across building levels remain largely unexplored. In response, this study adopts both mass and price as normalization factors for evaluating the circularity of building products and systems and provides a comparative analysis of how each factor influences assessment outcomes.

Adding factors to EBCI's SCI & BCI

At the building level, a normalization factor is essential for assessing circularity across different systems. This study introduces an additional variable called “renovation time,” which accounts for the number of times a system is replaced throughout the building’s lifecycle. Existing MCI-based BCIs typically only consider the initial use of materials in a building project, without providing a comprehensive evaluation of how various building systems influence circularity over the entire lifecycle (ISO, 2017). By integrating the renovation time factor into the assessment framework, this study ensures that the impact of systems with shorter lifespans is accurately reflected in the final building circularity score.

Summary of SCI & BCI

Three more steps are required for calculating SCI and BCI:

Step 1: Calculating PCI at the system level (i.e., PCIs):

$$PCIs = PCI * Ds \quad (12)$$

Ds: the disassembly factor. If cement, glue, or welding was used when joining different products at the system level, Ds=0.90, or else Ds=1.00



Step 2: Calculating SCI:

$$SCI = \frac{\sum PCIs * Nj * (RTj + 1)}{Ns} \quad (13)$$

Nj: the normalization factor (e.g., the weight or value) of different products in a system

RTj: the renovation time of a product throughout the building lifespan

Ns: the normalization factor (e.g., the weight or value) of the assessed system

$$RT = \frac{WBL}{L} - 1 \quad (14)$$

WBL: the expected building lifespan

L: the expected product lifespan

$$Ns = \sum Nj * (RTj + 1) \quad (15)$$

Step 3: Calculating BCI:

$$BCI = \frac{\sum SCI * Ns}{Nb} \quad (16)$$

Ns: the normalization factor (e.g., the weight or value) of the different systems

Nb: the normalization factor (e.g., the weight or value) of the assessed building

$$Nb = \sum Ns \quad (17)$$

2.2 Case Study

2.2.1 Case Selection

The concept of the circular economy began to gain popularity among the international society in 2010 following the release of several reports (Aggeri, 2020). This trend also emerged in Taiwan

around 2016, followed by the launch of the Circular Economy Program at the end of 2018 by Taiwan's central government, aiming to create new sustainable industries. In the meantime, both the private and public sectors in Taiwan started to embed this concept into their new building projects, aiming to transform Taiwan's building industry into a more sustainable one.

Taisugar Circular Village (TCV) stands as Taiwan's inaugural circular housing development, marking a significant milestone in the nation's pursuit of sustainable building practices (Tseng et al., 2021). The project's design phase commenced in the winter of 2017, followed by construction beginning in 2018 and reaching completion in the summer of 2021 (Tseng et al., 2021). Supported wholeheartedly by its project owner, the TCV design team implemented a range of strategies to enhance material circularity, such as utilizing recycled building materials, incorporating modular and reversible design principles, and adopting a Product-as-a-Service business model (see Figure 13~16). TCV was chosen as the subject of this study because it serves as a pioneering pilot project that integrates the broadest spectrum of circular approaches currently found in Taiwan (Tseng et al., 2021).

building site area	13,994.07 m ²
total floor area	28,532.76 m ²
total housing units	all types: 351 units studio type: 223 units (29 m ²) single room: 55 units (46 m ²) double room: 31 units (65 m ²) triple room: 42 units (106 m ²)
total parking space	166 for vehicle 445 for motorbike
total construction cost	1.23 billion NTD (40.72 million USD)



Figure 13. Basic information about Taisugar Circular Village



Figure 14. Circular Approaches in Taisugar Circular Village

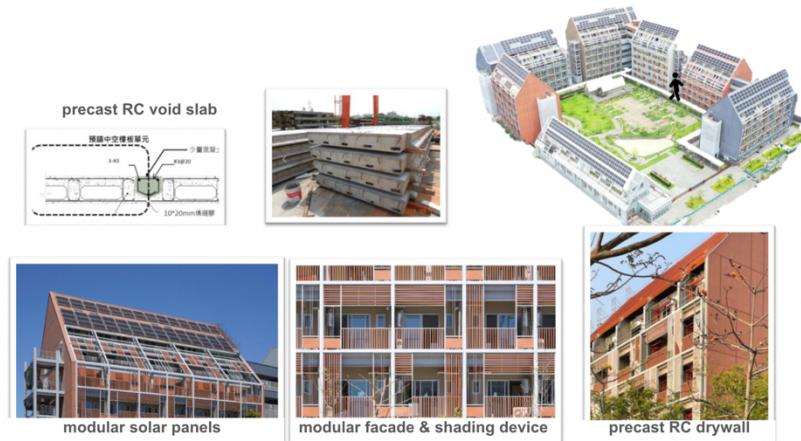
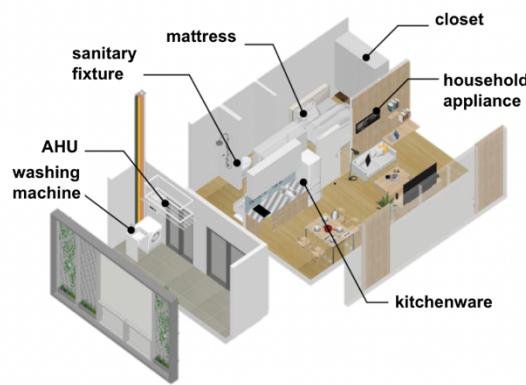


Figure 15. Modular Construction in Taisugar Circular Village



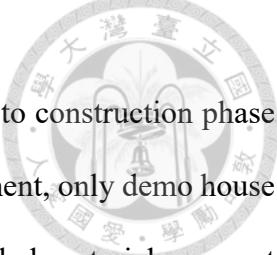
item	leasing period
elevator	20 yrs
sanitary fixture	10 yrs
lighting fitting	10 yrs
AHU	10 yrs
household appliance	10 yrs
smart door lock	10 yrs
food waste processor	10 yrs
furniture	6 yrs
mattress	6 yrs

Figure 16. Product-as-a-Service Model in Taisugar Circular Village

2.2.2 Data Collection

Although Building Information Modeling (BIM) was used from design to construction phase by designers and contractors for better project communication and management, only demo house (D-house) in TCV (see Figure 13) has an as-built BIM model and detailed material passport containing information related to production and maintenance of building materials and products provided by suppliers. D-house is also chosen by the project owner for circularity assessment, representing other buildings on site, which also becomes the scope of this study. The proportion of different building products in the D-house is slightly different from that in the other part of TCV. However, the types of building products used in D-house and the other parts are highly similar.

The data collection procedure for the case study, illustrated in Figure 17, comprises five main steps. Initially, the bill of quantities (BoQ) for the D-house was generated through a quantity take-off from its Building Information Modeling (BIM) model, providing fundamental details about each building product, such as name, quantity, and dimensions. Subsequently, key data needed to determine the weights of these products—such as mass ratios—were gathered with support from suppliers, allowing for accurate mass calculations. During this process, cost information specific to the D-house was extracted from the TCV budget documentation. The two resulting BoQ datasets were then consolidated into a single comprehensive list for further assessment. The BIM model used was developed at Level of Detail (LOD) 300, meaning its elements are visually represented as defined systems, objects, or assemblies, complete with detailed attributes like quantity, size, shape, location, and orientation. This level of detail is suitable for generating BoQs and cost estimates required for procurement, as it leverages the precise data embedded in the model (AIA, 2013). Models with an LOD below 300 may lack sufficient material information for effective Building Circularity Indicator (BCI) analysis, while those with an LOD above 300 can provide



even greater detail—such as construction methods—which is valuable for determining factors like disassembly potential (D_p , D_s).

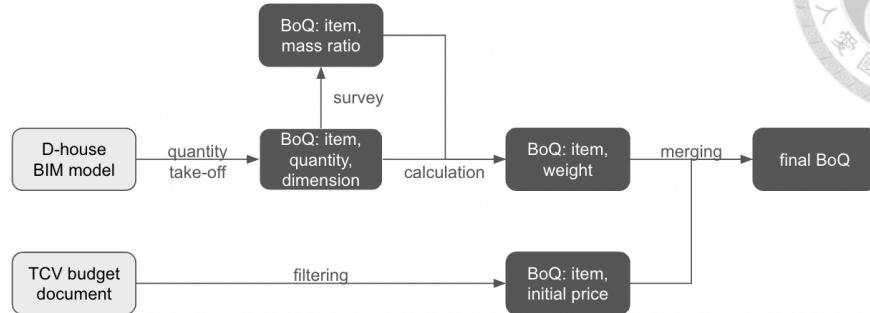


Figure 17. Data collection process in our case study

The data processing workflow for the case study, as depicted in Figure 18, consists of five main steps. First, after compiling the complete Bill of Quantities (BoQ) for the D-house, products were categorized into different systems according to their functional roles. Next, the proportions of these products within each system were determined by both mass and price, with items contributing less than 1% by either metric excluded from further analysis. Subsequently, key parameters relevant to the BCI were incorporated to facilitate the circularity assessment, enabling the calculation of the MCI, PCI, SCI, and the overall BCI for the case study. Figure 18 also outlines the data sources used for these parameters: firsthand data such as audited supplier reports or certificates are prioritized. If such data are unavailable, secondary sources—including published reports on typical recycling rates and product lifespans—are utilized. In cases where both firsthand and secondhand data are lacking, the study relies on assumed parameters, such as estimated recycling ratios for PaaS models.



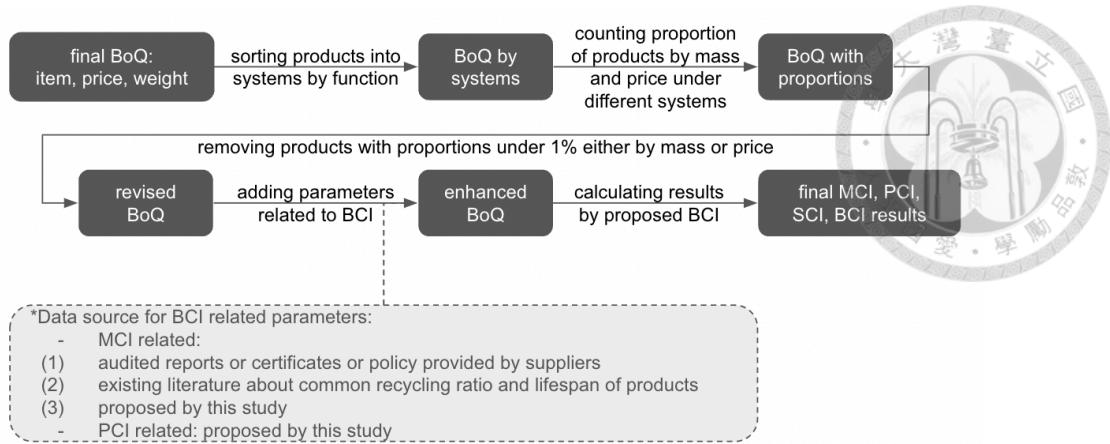


Figure 18. Data processing process in our case study

3. Results

3.1 Assessment at the Material Level

3.1.1 Building Materials in TCV's Structural System

The structural system of the study case is made of two parts: (1) steel frames composed of steel sections and (2) precast void RC slabs (see Figure 19). Different parameters used for calculating the MCI and MCIP of these building products are shown in Table A1 in the Appendix.

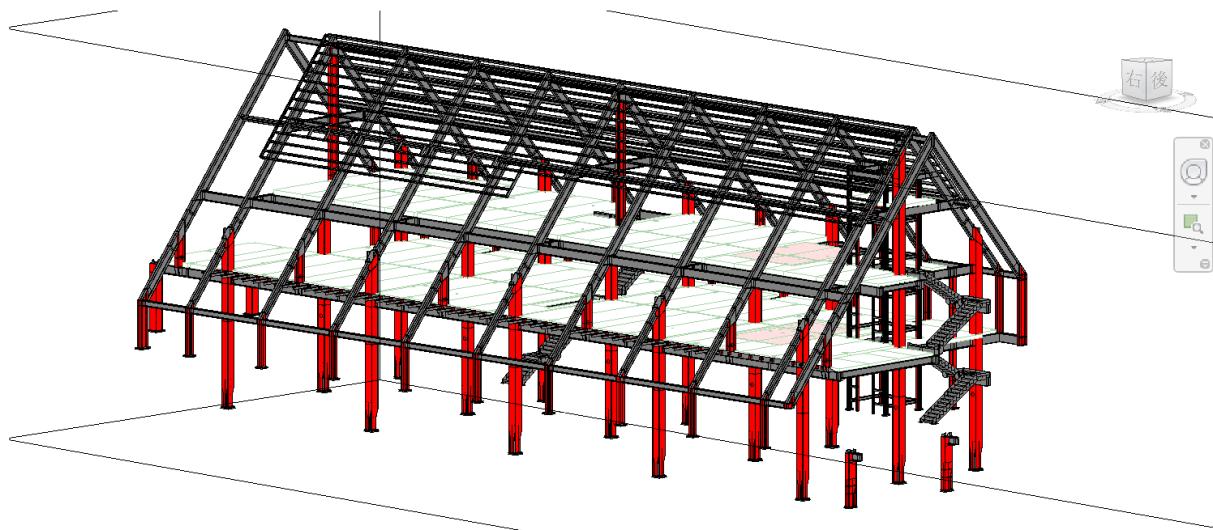


Figure 19. Structural components of study case in BIM

The following is more information about the parameters used in the calculation. Using blast-furnace cement and electric-furnace steel bars is common in Taiwan for constructing reinforced concrete (RC) structures. Thus, the feedstock fractions derived from recycled sources (F_R) for concrete and steel bars are calculated as 5% and 80%, respectively. Regarding the end-of-life phase, according to Taiwan's construction regulations, all the wasted concrete should be collected and transported to registered plants. Based on a nationwide survey, approximately 75% of wasted

concrete is recycled and reused in new construction sites, while 25% is sent to landfills. As for steel bars, since the economic value of recycled steel is high in Taiwan, their recycling rate is as high as 90%. Hence, the fractions of the mass collected for recycling (C_R) are set as 75% and 90% for concrete and steel bars, respectively. The efficiency of the recycling process employed to produce the recycled feedstock (E_F) and used to recycle the product at the end of its use phase (E_C) is set as 0.90, following EMF's suggestion (EMF & Granta Design, 2019). Meanwhile, steel sections manufactured via blast furnaces and electric furnaces are common in Taiwan, with recycled feedstock (F_R) levels of 0% and 80%, respectively.

Using the parameters outlined above and adhering to the original MCI formula, the Material Circularity Indicator for a typical reinforced concrete (RC) slab (MCIp) is calculated as 0.46 (see Figure 20). However, this value does not account for the downcycling of waste concrete. By integrating the recycling level factor ($L_v = 0.80$) into the revised MCI formula proposed in this study, the MCIp for a standard RC slab decreases to 0.33. In the case study, precast void RC slabs—lighter than conventional slabs—are employed. Incorporating the lightweight design factor ($L_w = 0.90$) into the calculation raises the MCIp result to 0.39. For the steel sections used in the project, which are made of blast-furnace steel, the calculated MCIp is 0.47. If electric furnace steel (with a recycled content fraction $F_R = 80\%$) were substituted, the MCIp would increase significantly to 0.82, underscoring the impact of material choice on circularity outcomes.

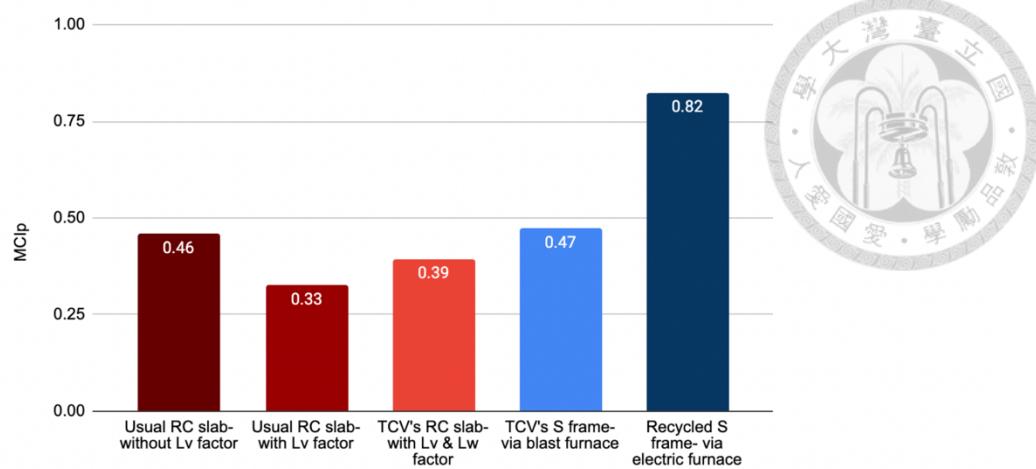


Figure 20. MCIp of different building products in the structural system under different calculation scenarios

3.1.2 Building Materials in TCV's Exterior System

The exterior system in this case study consists of three main components: (1) pitched roofs constructed from steel panels, (2) dry walls composed of reinforced concrete (RC) walls and tiles, and (3) curtain walls featuring aluminum frames, panels, and glass windows (see Figure 21). The specific parameters applied for calculating the MCI and the MCIp for these building elements are detailed in Table A2 of the Appendix.

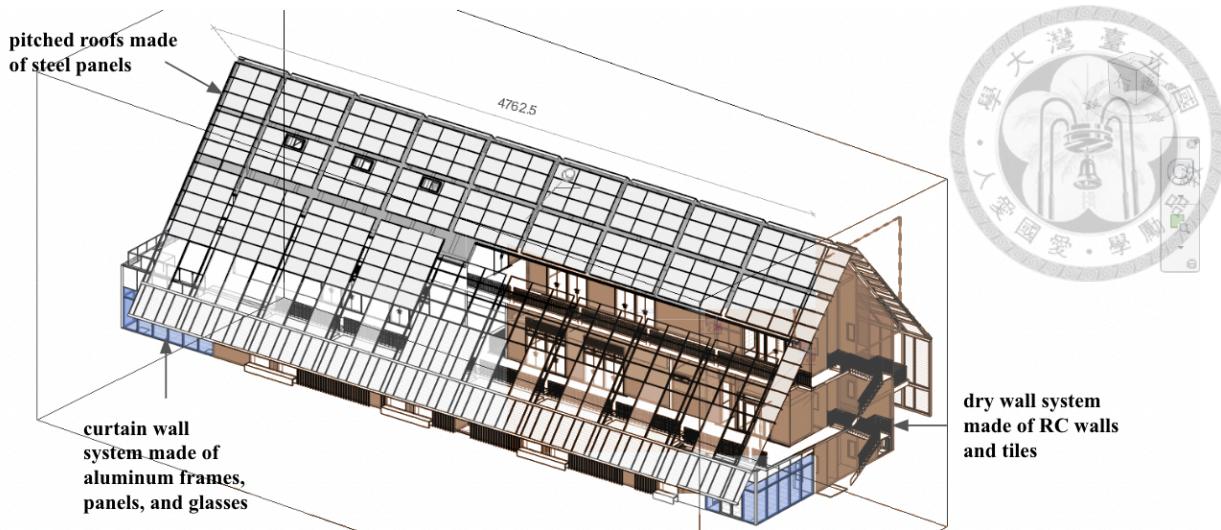


Figure 21. Exterior components of study case in BIM

The following is more information about the parameters used in the calculation. Like the steel sections used in the structural system, the steel panels of the pitched roofs in the exterior system are also made of blast-furnace steel manufactured from virgin stock in Taiwan; thus, their F_R is 0.00. The dry walls of the study case are composed of RC walls and tiles manufactured in a factory and assembled onsite. These ceramic tiles are not produced from recycled feedstock; thus, their F_R is 0.00. Since they are fixed to RC walls, they are collected with the waste concrete after demolition. Hence, its C_R is set as 0.75. However, since ceramic tiles can be manufactured from waste construction surplus soil, the recycle level (Lv) factor is not applied.

Meanwhile, the curtain walls of the study case are composed of aluminum frames and glasses. The former are commonly manufactured from imported secondary aluminum ingot, and their F_R is set as 0.08. As for the latter, the single clear glass is manufactured with 20% recycled feedstock, as stated in the manufacturer's CSR report. Nevertheless, the special double glass is produced differently without recycled feedstock. Although the recycling rates for aluminum frames and glasses after their end of life are high (around 90%), according to a national survey, discarded

glasses are mostly used to manufacture other glass products with lower economic value (e.g., glass containers). Hence, the factor of recycling level (Lv) is also applied.

Besides the factor of recycling level, the extended lifespan (L/Lav) has a noticeable impact on the MCIp result. The average lifespan (Lav) for a building façade is set to be 30 years, while the lifespan of dry walls in our study case is the same as the building lifespans (L = 60). Hence, their L/Lav increases from 1.00 to 2.00, and their MCIp from 0.33 to 0.66. Meanwhile, the average lifespan (Lav) for a building roof is set to be 20 years, while the lifespan of pitched roofs in our study case is extended because they have a special coating and are covered by solar panels. Hence, their L/Lav increases from 1.00 to 1.50, and their MCIp from 0.47 to 0.65.

Based on the abovementioned parameters, the MCIp results of different building products in the exterior system are shown in Figure 22. Window components have lower MCIp results due to the lower MCI of the glass part, whereas the other curtain wall components have higher results because of the higher MCI of the metal part. The MCIp results for drywalls and pitched roofs are increased due to the extended lifespan (L/Lav).

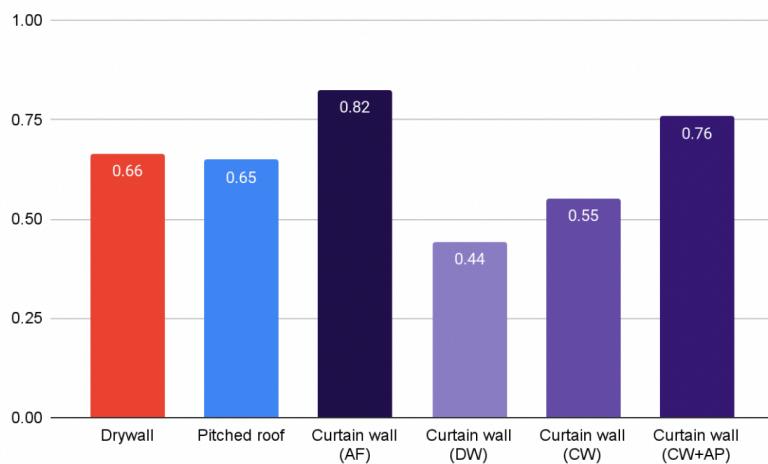


Figure 22. MCIp of different building products in the exterior system

3.1.3 Building Materials in TCV's Interior System

The interior system in this case study comprises five primary components: (1) ceramic tiles set with cement mortar, (2) raised flooring systems constructed from galvanized steel channels and PVC boards, (3) four varieties of dry partition walls utilizing iron channels, rockwool, gypsum and cement boards, as well as crystal tiles, (4) three types of concealed ceilings made with iron channels, calcium silicate and wood cement boards, and expanded metal mesh, and (5) two categories of doors featuring wooden and galvanized steel panels (see Figures 23–25). For the purposes of this assessment, doors are excluded due to their relatively minor contribution to the total mass. The parameters employed for calculating the MCI and MCIP for these interior building elements are provided in Table A3 of the Appendix.

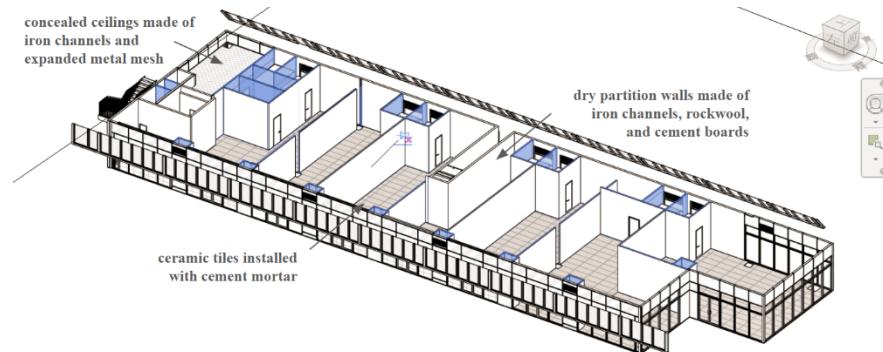


Figure 23. Interior components on the 1st floor of study case in BIM

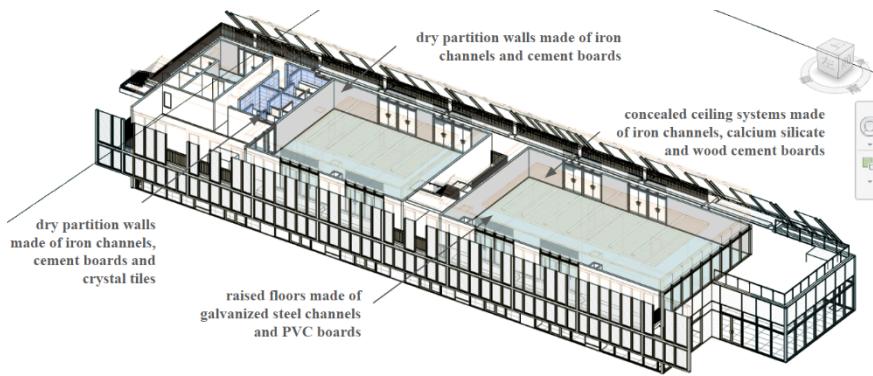


Figure 24. Interior components on the 2nd floor of the study case in BIM

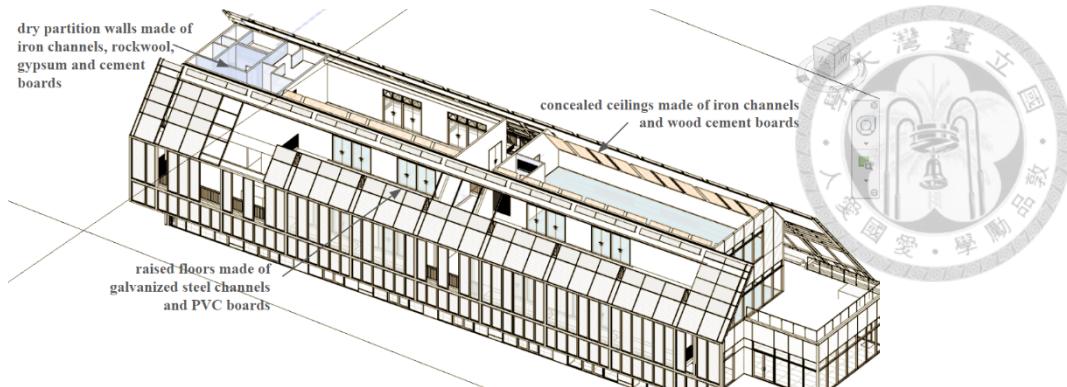


Figure 25. Interior components on the 3rd floor of study case in BIM

The following is more information about the parameters used in the calculation. First, two types of flooring are constructed in our study case: ceramic and raised flooring. Regarding the former, there is no recycled feedstock for both ceramic tiles and cement mortar, and it is typically treated as waste concrete after demolition; hence, its F_R and C_R are set as 0.00 and 0.75, respectively. Regarding the latter, the ratio of recycled feedstock for PVC boards and galvanized steel channels is 0% and 40%, respectively. In contrast to the high recycling rate of galvanized steel ($C_R = 0.90$), the C_R is low for PVC boards ($C_R = 0.10$) because their economic value is low after their end of life.

Second, four types of dry partition walls are constructed, utilizing iron channels to support and cover three types of materials. No recycled feedstock is used to produce the gypsum, cement boards, and crystal tiles used in our study case. And like the wasted clay tiles, they are usually treated with wasted concrete after demolition. Hence, their F_R and C_R are set as 0.00 and 0.75, respectively. Unlike cement boards, gypsum boards and crystal tiles cannot be manufactured from waste construction surplus soil. Hence, the recycle level (Lv) factor is applied to both materials. Regarding rockwool, since no recycled feedback is used in its production and it typically ends up in a landfill in Taiwan, its F_R and C_R are both 0.00.

Third, three types of concealed ceilings are constructed, utilizing iron channels to support and hold various types of covering. The calcium silicate boards used in TCV are certified green building materials, with 50% of recycled feedstock used in their manufacturing, whereas the wood cement boards are not. Hence, their F_R are 0.50 and 0.00, respectively. Both types of boards are usually treated with wasted concrete after demolition. Nevertheless, since they can be manufactured from waste construction surplus soil, L_v is not applied.

Based on the parameters, the MCI_p of ceramic and raised PVC flooring are calculated as 0.34 and 0.47, respectively (see Figure 26). Although the MCI of PVC boards is low (0.14), their weight is significantly smaller than that of galvanized steel channels, which have a much higher MCI (0.65); thus, the MCI_p of PVC flooring is higher than that of ceramic flooring.

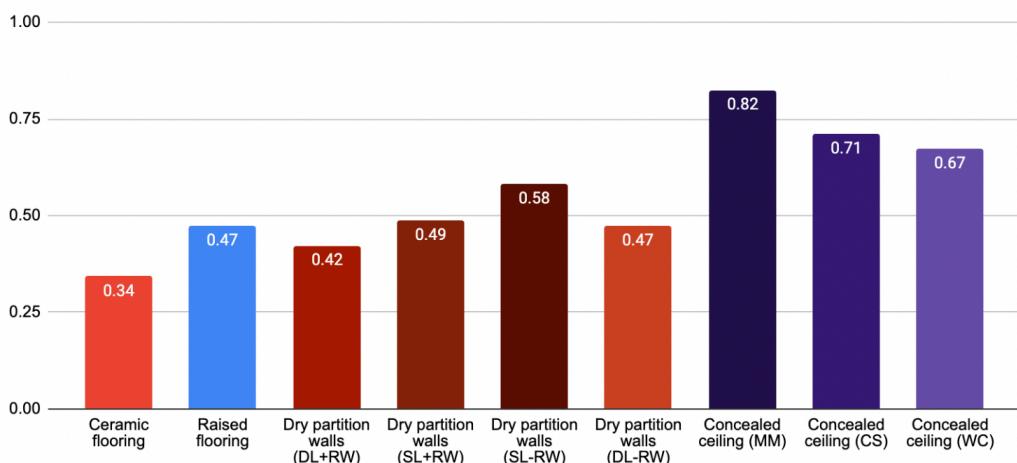


Figure 26. MCI_p of different building products in the interior system

Among the four dry partition wall types analyzed, double-sided walls exhibit lower MCI_p (MCI_p = 0.42 and 0.47) compared to single-sided walls (MCI_p = 0.49 and 0.58). This discrepancy arises because double-sided walls incorporate gypsum boards and crystal tiles, which have inherently lower MCIs due to downcycling and higher mass. While rockwool—used in these walls—has the lowest MCI (0.19) among all materials, its lightweight nature minimizes its overall

impact on the results. Increasing the use of recycled feedstocks in manufacturing the wall's covering boards could significantly improve their MCIP. Additionally, applying the lightweight design factor (L_w) boosts the MCIP of these walls by approximately 0.05, as they are lighter than conventional reinforced concrete (RC) and brick walls commonly used in Taiwan.

The MCIP for the three types of concealed ceilings is higher than that of other interior building products, primarily due to the use of covering boards with higher circularity—such as calcium silicate boards containing 50% recycled feedstock—or the incorporation of lighter materials like wood cement boards. The MCIP values for these ceilings could be further improved by increasing the proportion of recycled feedstocks used in their production and by enhancing recycling rates at the end-of-life stage for the covering boards.

3.1.4 Building Materials in TCV's Service System

The service system of the study case is made of five parts: (1) a heating, ventilation, and air conditioning (HVAC) system, (2) electrical engineering, (3) water supply (WS) engineering, (4) wastewater (WW) engineering, and (5) fire protection (FP) engineering (see Figure 27). However, FP engineering is excluded from the assessment because the number of products and the type of materials are very limited by the fire regulations in Taiwan. Different parameters used for calculating the MCI and MCIP of these building products are shown in Table A4 in the Appendix.

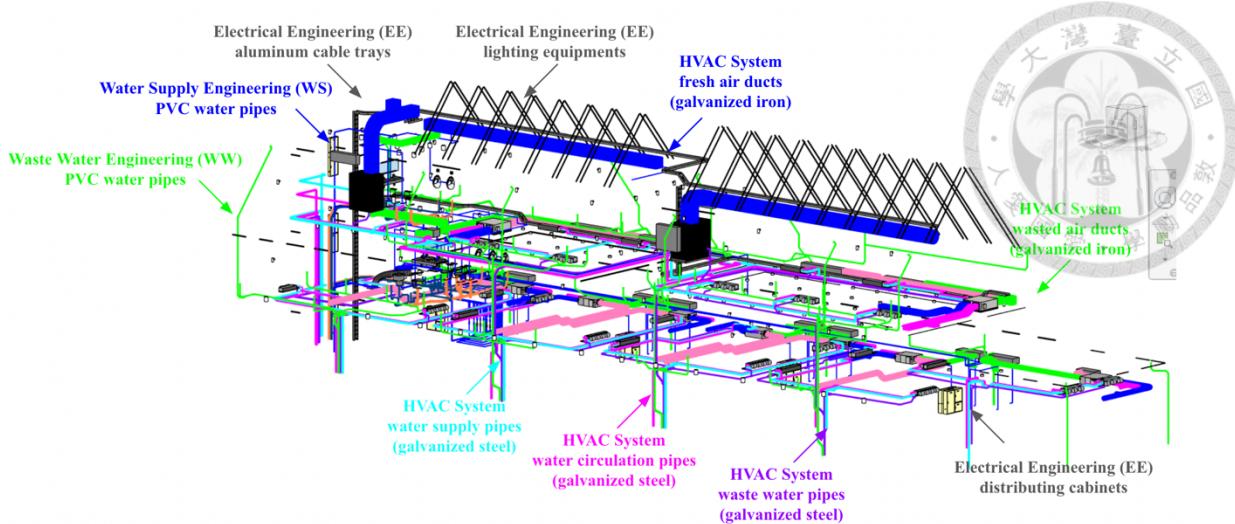


Figure 27. Service components of study case in BIM

Additional details regarding the parameters used in the calculation are provided here. As the first circular housing development in Taiwan, Taisugar Circular Village (TCV) implemented a Product-as-a-Service (PaaS) model within its service system, allowing for the rental of air handling units, lighting fixtures, and sanitary fixtures. This business model offers two main advantages: (1) it significantly increases the likelihood that these products will be reused or remanufactured, and (2) it ensures better maintenance, thereby extending the lifespan of the products. To account for these benefits in the assessment, the component reuse fraction (C_U) for these rented building products is set at 100%, and their length component (L/Lav) is assigned a value of 150%. Using these parameters, the product-level Material Circularity Indicator (MCI_p) for these items is calculated to be 0.70.

In addition to the rented air handling units, the HVAC system is mainly composed of air ducts made from galvanized iron panels and water pipes constructed from galvanized steel. According to national survey data, these components have a recycled feedstock ratio (F_R) of 0.40 and a closed-loop recycling rate (C_R) of 0.90, resulting in a MCI_p of 0.65 (see Figure 28).

For the electrical engineering system, aside from the rented lighting fixtures, the primary elements include distribution cabinets—composed of complex materials—and aluminum cable trays. The distribution cabinets are acquired through traditional procurement methods, and due to the intricate nature of their internal materials, both the component reuse fraction (C_U) and closed-loop recycling rate (C_R) are set at 0.00, yielding an MCIP of 0.10. In contrast, national survey findings indicate that the aluminum cable trays possess an FR of 0.80 and a CR of 0.90, resulting in a notably higher MCIP of 0.82.

In addition to the rented sanitary fixtures, the water supply and wastewater systems are primarily composed of polyvinyl chloride (PVC) water pipes. Due to the absence of recycled feedstock in their production and their low economic value at the end of their lifecycle, both the recycled feedstock ratio (F_R) and closed-loop recycling rate (C_R) for these pipes are set to 0.00, resulting in a product-level Material Circularity Indicator (MCIP) of 0.10.

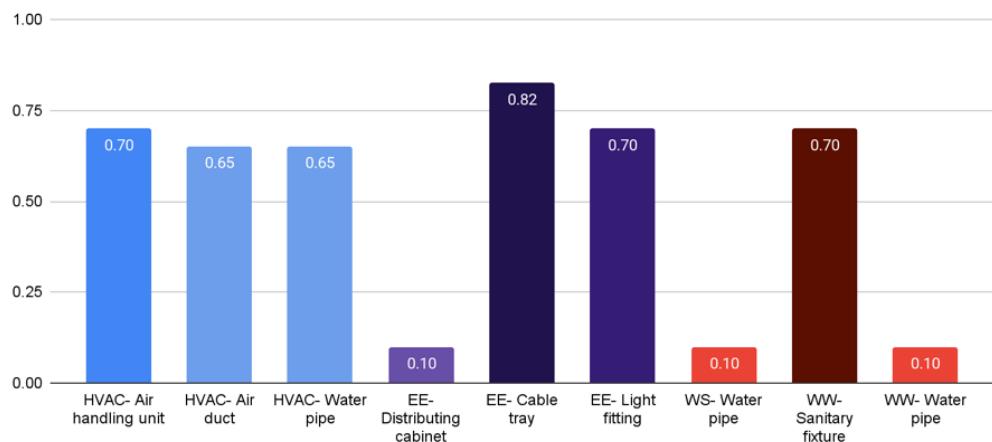


Figure 28. MCIP of different building products in the service system

3.2 Assessment at the Product Level

3.2.1 Building Products in TCV's Structural System

To evaluate the circularity of building products, this study incorporates both the disassembly factor (D_p) and the modularity factor (M_d) alongside the product-level Material Circularity Indicator (MC I_p). As detailed in Section 3 Methods, the assessment of D_p has been streamlined to reflect Taiwan's specific environmental conditions and prevailing construction practices. When cement, adhesives, or welding are used in the assembly of a building product, a deduction coefficient of 0.80 is applied to the calculation. Similarly, the approach for assessing M_d is simplified: if a product's dimensions are predetermined during the design phase and the product is manufactured in a factory setting, an appreciation coefficient of 1.10 is included in the calculation.

The parameters used to calculate the Product Circularity Indicator (PCI) and adjusted PCI (PCI') for building products in the structural system are detailed in Table A5 of the Appendix. In this case study, steel sections and reinforced concrete (RC) slabs are modularized and factory-manufactured, leading to a modularity factor (M_d) of 1.10. However, since RC slabs are assembled using cement, their disassembly factor (D_p) is set to 0.80, whereas steel sections retain a D_p of 1.00. After applying these adjustments, the PCI' for steel sections increases from 0.47 to 0.52, while the PCI' for RC slabs decreases from 0.39 to 0.35 (see Figure 29). For comparison, conventional RC components—typically cast onsite—have no modularity adjustment ($M_d = 1.00$) and a lower disassembly factor ($D_p = 0.80$), resulting in a PCI' reduction from 0.33 to 0.26.



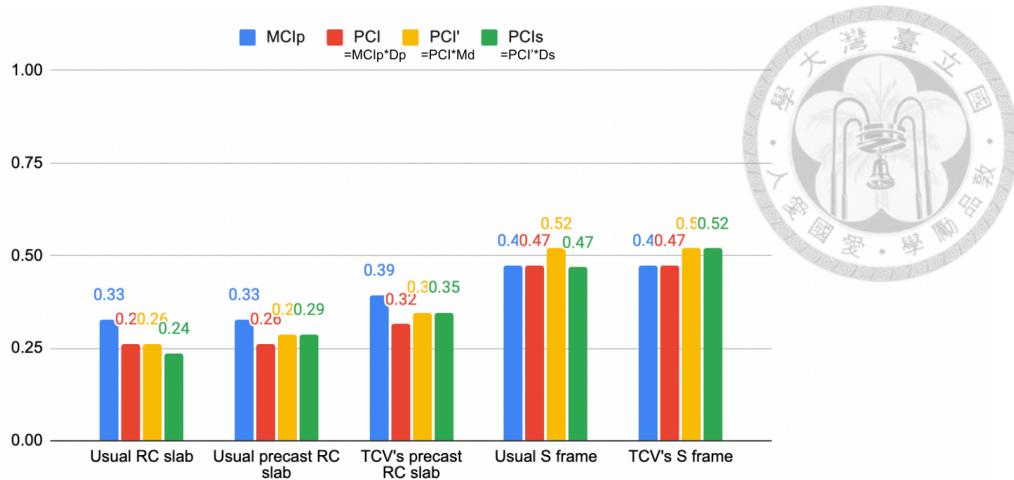
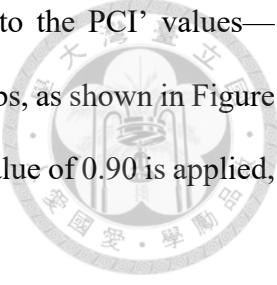


Figure 29. PCI, PCI' and PCIs of different building products in the structural system

To evaluate the circularity of building systems, it is critical to account for interdependencies between products both within and across systems (van Vliet, 2018). For this reason, the disassembly factor at the system level (Ds) is introduced alongside the adjusted Product Circularity Indicator (PCI'). Mirroring the approach used for Dp, this study employs a streamlined method to assess Ds, tailored to Taiwan's unique environmental constraints and construction norms. If cement, adhesive, or welding is utilized to connect building products within or between systems, a deduction coefficient of 0.90 is applied. This adjustment reflects the reduced potential for system-level disassembly and reuse, which is particularly relevant in contexts prioritizing seismic resilience through traditional assembly techniques.

The parameters utilized for calculating the Product Circularity Indicators (PCIs) of structural building products are detailed in Table A5 of the Appendix, with the corresponding results also presented in this section and illustrated in Figure 29, alongside PCI and PCI' values to clarify the effects of the disassembly (Dp), modularity (Md), and system disassembly (Ds) factors on building circularity. In this case study, all structural components are assembled using screw connections,

resulting in a D_s value of 1.00 and ensuring that the PCIs are identical to the PCI' values—specifically, 0.52 for steel sections and 0.35 for reinforced concrete (RC) slabs, as shown in Figure 29. Conversely, for conventional RC components constructed onsite, a D_s value of 0.90 is applied, which lowers their PCIs from 0.26 to 0.24.



3.2.2 Building Products in TCV's Exterior System

The exterior system consists of three primary components: pitched roofs constructed from steel, drywalls made of reinforced concrete (RC) with tile finishes, and curtain walls featuring aluminum frames. The parameters used for calculating the Product Circularity Indicator (PCI) and its adjusted value (PCI') for these elements are detailed in Table A6 of the Appendix. All of these products are modularized and produced in factories, resulting in a modularity factor (M_d) of 1.10 for each. However, since the assembly of the RC drywalls involves the use of cement, their disassembly factor (D_p) is set at 0.80, while the D_p for both the pitched roofs and curtain walls remains at 1.00. Taking these factors into account, the PCI' for the pitched roofs increases from 0.65 to 0.71, and for the two types of curtain windows—dormant and common windows—the PCI' rises from 0.44 to 0.49 and from 0.55 to 0.61, respectively (see Figure 30). In contrast, the PCI' for RC drywalls decreases from 0.66 to 0.58 due to the lower D_p value associated with their assembly method.

The parameters used to calculate the system-level Product Circularity Indicators (PCIs) for exterior building products are detailed in Table A6 of the Appendix. In this case study, all exterior components are assembled using screw connections, resulting in a system disassembly factor (D_s) of 1.00. Consequently, their PCIs remain unchanged from the adjusted product-level values (PCI'), as illustrated in Figure 30.

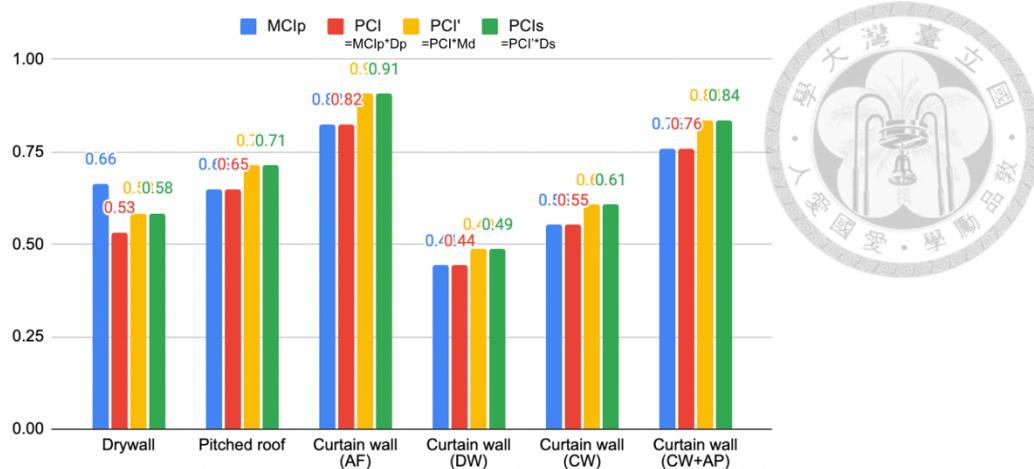


Figure 30. PCI, PCI' and PCIs of different building products in the exterior system

3.2.3 Building Products in TCV's Interior System

Within the interior system, the assessment encompasses four varieties of dry walls, three ceiling types, and two flooring types, with the specific parameters used for calculating their Product Circularity Indicator (PCI) and adjusted PCI (PCI') detailed in Table A7 of the Appendix. All these components are modularized and factory-produced, resulting in a modularity factor (Md) of 1.10 being applied across the board. However, because the installation of ceramic flooring and dry partition walls with crystal tiles utilizes cement, their disassembly factor (Dp) is set at 0.80, whereas the Dp for the remaining interior products is maintained at 1.00. After factoring in both Dp and Md, the PCI' for ceramic flooring and dry partition walls with crystal tiles (DL-RW) decreases from 0.34 to 0.27 and from 0.47 to 0.42, respectively. In contrast, the PCI' for the other three types of partition walls, as well as all three ceiling types and the raised flooring, increases by 10% due to the application of the modularity factor.

The various parameters applied for calculating the PCIs of interior building products are detailed in Table 7 of the Appendix. In this case study, only ceramic floorings are joined to other

building products using cement, resulting in a system disassembly factor (Ds) of 0.90 for these elements and a corresponding reduction in their PCIs from 0.27 to 0.25. In contrast, all other interior components are assembled with screw connections, so their Ds remains at 1.00, and their PCIs are unchanged from the PCI', as shown in Figure 31.

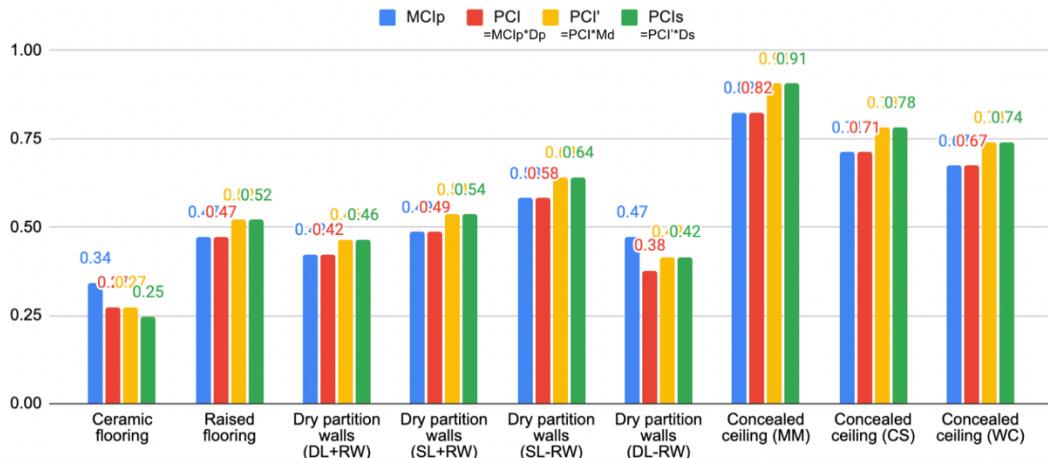


Figure 31. PCI, PCI' and PCIs of different building products in the interior system

3.2.4 Building Products in TCV's Service System

The services system assessment includes four subsystems comprising pipes, ducts, cable trays, and equipment. Parameters for calculating their Product Circularity Indicator (PCI) and adjusted PCI (PCI') are provided in Table A8 of the Appendix. Since none of these components are assembled using cement, their disassembly factor (Dp) is set to 1.00. However, PVC water pipes—whose dimensions were not predefined during the design phase and are cut onsite—retain a modularity factor (Md) of 1.00, while all other components receive an Md of 1.10. After applying these factors, the PCI' for PVC water pipes remains unchanged at 0.10, whereas the PCI' for the remaining components (e.g., galvanized steel ducts, aluminum cable trays) increases by 10%, as illustrated in Figure 32.

The parameters applied for calculating the Product Circularity Indicators (PCIs) of service system building products are detailed in Table A8 of the Appendix. In this case study, sanitary fixtures are the only components connected to other building products with cement, resulting in a system disassembly factor (Ds) of 0.90 and a corresponding reduction in their PCIs from 0.77 to 0.69. In contrast, all other service system components are assembled using screw connections, so their Ds remains at 1.00, and their PCIs are unchanged from the PCI', as illustrated in Figure 32.

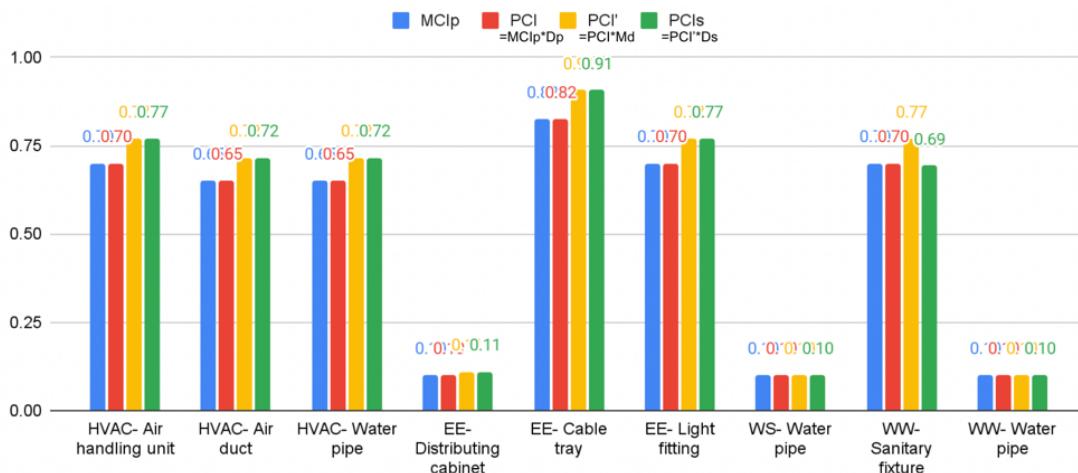


Figure 32. PCI, PCI' and PCIs of different building products in the service system

3.3 Assessment at the System Level

3.3.1 TCV's Structural System

After considering the disassembly factor (Ds), the normalization factor (N) is used to summarize the circularity of building products at the system level, i.e., the circularity of building systems (SCI). In this study, both the mass (M) and price (E) of building products are used for normalization. The different SCI results based on both normalization factors, i.e., SCI(M) and SCI(E), are presented for further comparisons and discussions.

As illustrated in Figure 33, steel sections exhibit a higher PCI compared to reinforced concrete (RC) slabs in the TCV. While steel sections also have a greater initial economic value (i.e., purchase price), their total mass is significantly lower than that of RC slabs. Consequently, when mass is used as the normalization factor for calculating the SCI of the structural system, the result is 0.07 lower than when price is employed as the normalization factor. This disparity highlights how the choice of normalization factor influences circularity assessments, particularly when balancing material efficiency against economic value.

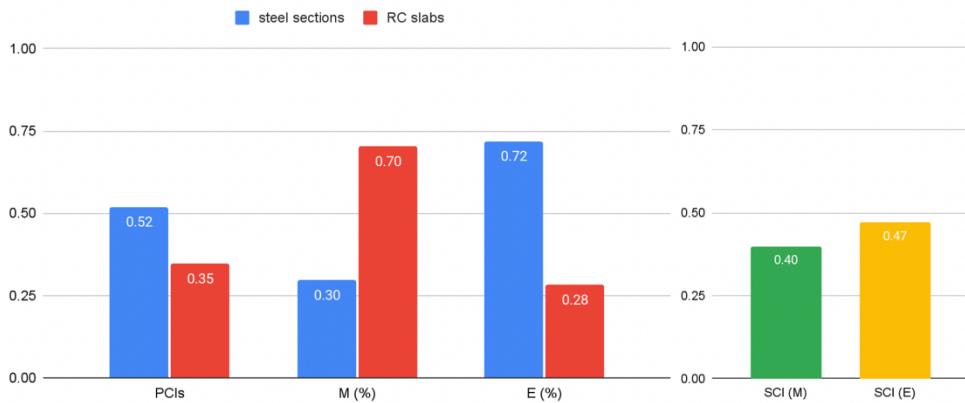


Figure 33. PCIs and proportions in mass and price of building products in structural system, and SCI of TCV's structural system normalized by total mass and price

This study places a strong emphasis on whole lifecycle analysis (WLCA), incorporating the RTs factor into the calculation of building product circularity at the system level for products with varying lifespans. For instance, if a building is expected to last 60 years and a particular product within it has a lifespan of 20 years, the RTs for that product would be counted as three—representing the number of times it needs to be replaced in addition to the initial installation. The section presents and discusses the differences in SCI results both with and without the inclusion of RTs. However, for structural components whose expected lifespan matches that of the building, the RTs value is 0.00, resulting in no difference in SCI outcomes for the structural system.

3.3.2 TCV's Exterior System

Before Considering Renovation Times (RTs)

As shown in Figure 34, although the PCIs of drywalls are relatively low compared to other building products in the exterior system, their mass accounts for a significant portion of the total. In contrast, although the curtain walls account for a comparatively low proportion of the total mass, their economic value is noticeable. Therefore, the SCI(M) of the exterior system is lower than SCI(E), and the difference between them reaches 0.08.

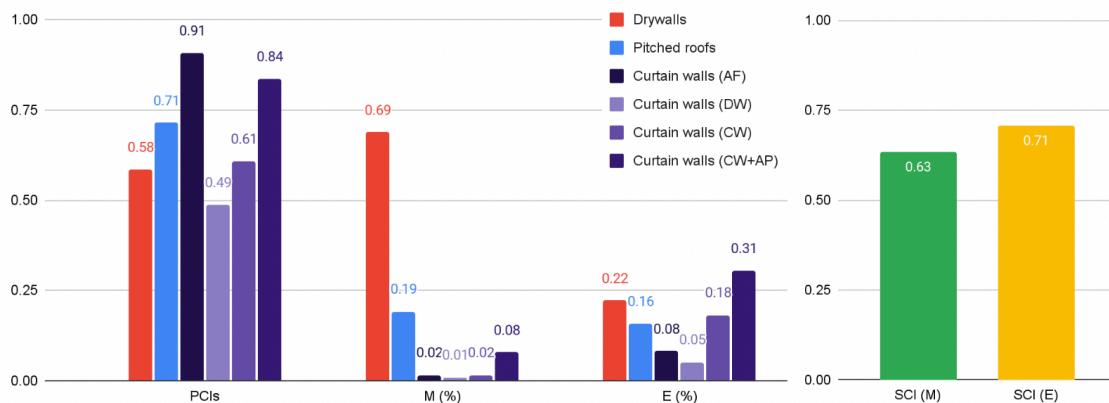


Figure 34. PCIs and proportions in mass and price of building products in the exterior system and SCI of TCV's exterior system normalized by total mass and price

After Considering Renovation Times (RTs)

Figure 35 presents the expected lifespans (L) of building products in the exterior system of TCV, alongside the industry average lifespans (Lav) of comparable products. By evaluating the ratio of L to Lav, the degree of lifespan extension (L/Lav) for each product is determined. Additionally, comparing each product's expected lifespan (L) to the overall projected lifespan of TCV (60 years) allows for the calculation of renovation times (RTs). As illustrated in Figure 35, all exterior components—except for the drywalls in this case study—are anticipated to require

replacement once during the building's lifecycle. Consequently, in accordance with the WLCA framework, the total mass and price of these products must be accounted for twice, which in turn influences the results of the SCI based on mass (SCI(M)) and economic value (SCI(E)).

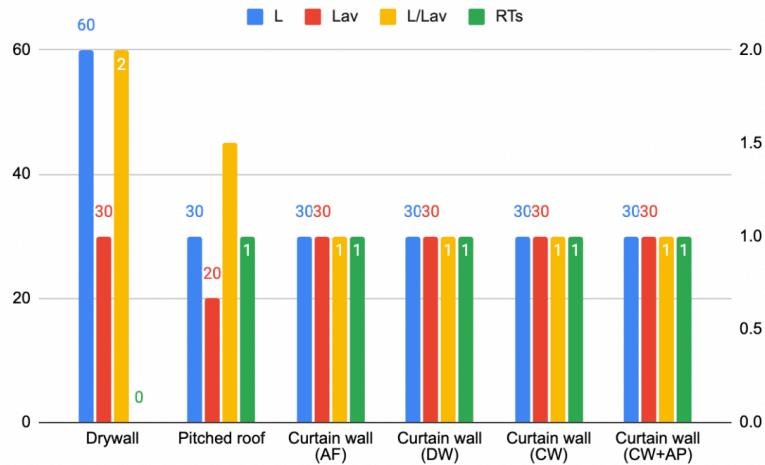


Figure 35. L, Lav, L/Lav, and RTs of building products in the exterior system

As illustrated in Figure 36, incorporating renovation times (RTs) leads to a reduction in the total mass and price attributed to drywalls, resulting in a corresponding increase of 0.03 in the SCI(M) and 0.01 in the SCI (E) for the exterior system. However, these changes are minor.

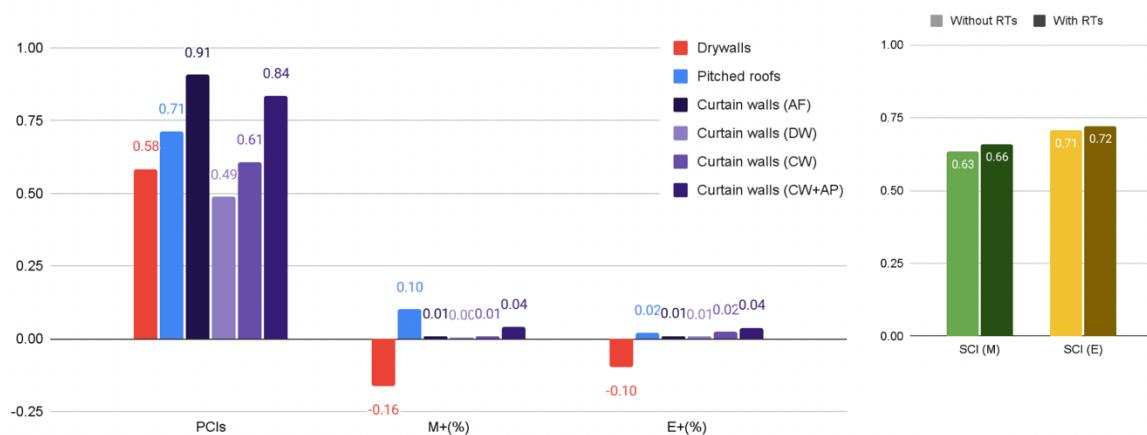


Figure 36. PCIs and increased/decreased proportions in mass and price of building products in the exterior system and SCI of TCV's exterior system normalized by total mass and price before and after considering RTs

3.3.3 TCV's Interior System

As shown in Figure 37, ceiling components demonstrate higher PCIs compared to other elements in the interior system. However, their limited contribution to the system's total mass and price results in a negligible impact on both the mass-normalized (SCI(M)) and price-normalized (SCI(E)) System Circularity Indicators. Dry partition walls, while exhibiting average PCIs, dominate the system's total mass, making their influence on SCI(M) substantial. Conversely, raised flooring—despite having moderate PCIs—accounts for a significant portion of the system's total price, thereby exerting a pronounced effect on SCI(E). The final SCI(M) and SCI(E) for the interior system are calculated as 0.50 and 0.52, respectively, with only a minor discrepancy between the two metrics.

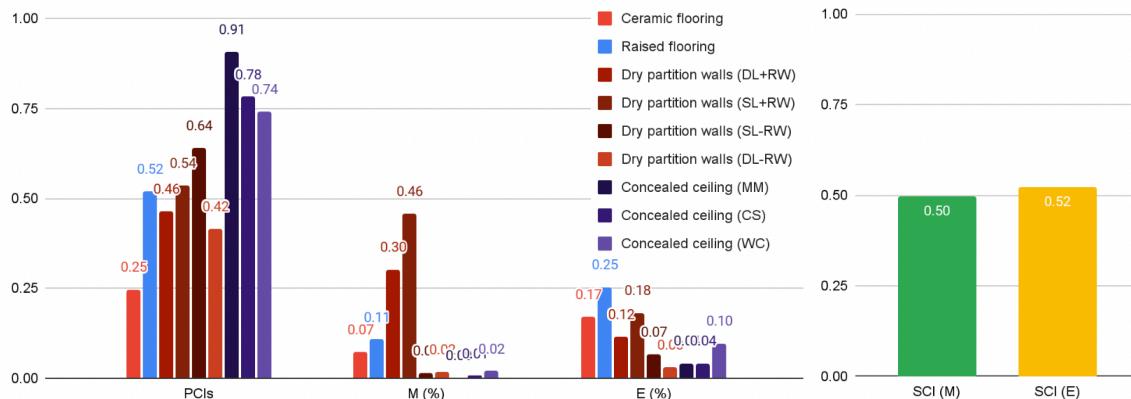


Figure 37. PCIs and proportions in mass and price of building products in the interior system and SCI of TCV's interior system normalized by total mass and price

Because all interior components have the same expected lifespan of 20 years, their renovation times (RTs) are uniformly counted as two cycles within the building's lifecycle. As a result, incorporating RTs does not alter the SCI outcomes for the interior system. However, the increased mass and price associated with the interior systems under the WLCA framework will influence the overall BCI, a topic that will be addressed in the following subsection.

3.3.4 TCV's Service System



Before Considering Renovation Times (RTs)

As illustrated in Figure 38, the components of the HVAC system in TCV exhibit high Product Circularity Indicators (PCIs) and contribute substantially to both the total mass and price within the service system. Consequently, the circularity performance of the HVAC system plays a pivotal role in determining both the mass-based (SCI(M)) and economic value-based (SCI(E)) System Circularity Indicators. In contrast, within the electrical engineering (EE) system, cable trays and lighting fittings demonstrate relatively high PCIs, whereas distribution cabinets display very low PCIs. Although distribution cabinets represent only a minor share of the system's total mass and price, their low circularity scores still exert a discernible influence on both SCI(M) and, more notably, SCI(E). Regarding the water supply (WS) and wastewater (WW) systems, while the water pipes have low PCIs, their minimal contribution to overall mass and price results in a negligible effect on both SCI(M) and SCI(E). Ultimately, the SCI(M) and SCI(E) for the service system in this case study are calculated as 0.69 and 0.67, respectively, with only a slight difference observed between the two metrics.

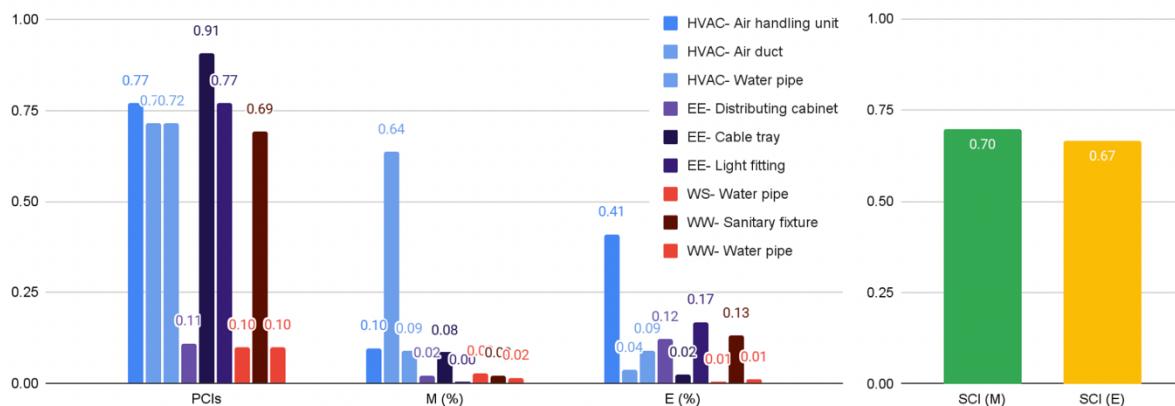


Figure 38. PCIs and proportions in mass and price of building products in service system, and SCI of TCV's service system normalized by total mass and price

After Considering Renovation Times (RTs)

Figure 39 presents the expected lifespans (L) of building products in the TCV service system, alongside the industry average lifespans (Lav) for comparable products, the extended lifespan factor (L/Lav), and the renovation times (RTs) for each component. As illustrated, both the L values and RTs differ across the various service system components, reflecting the diversity in product durability and replacement frequency. According to the whole lifecycle analysis (WLCA) framework, the total mass and price of these products must be accounted for multiple times in accordance with their respective RTs, ensuring a comprehensive evaluation of their lifecycle impacts. These variations directly influence the mass-based System Circularity Indicator (SCI(M)) and the economic value-based System Circularity Indicator (SCI(E)), underscoring the importance of considering lifespan and renovation frequency in circularity assessments.

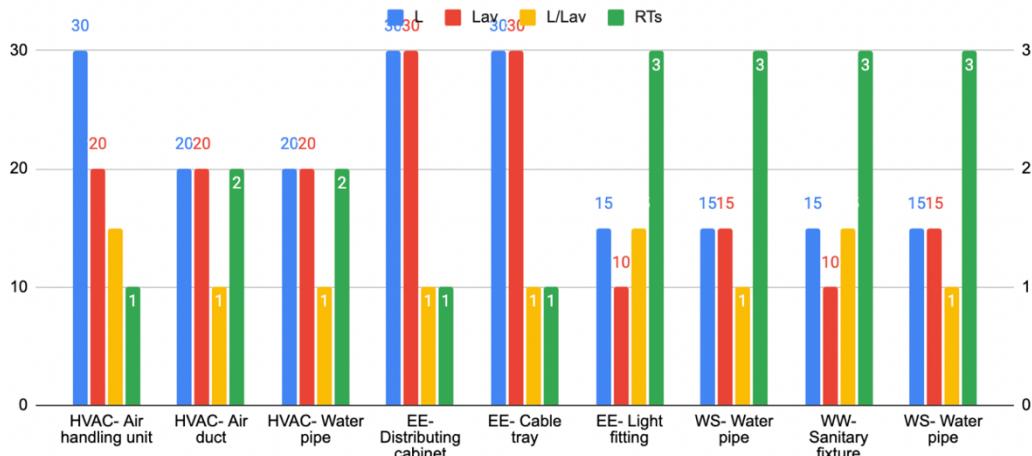


Figure 39. L, Lav, L/Lav, and RTs of building products in the service system

As depicted in Figure 40, incorporating renovation times (RTs) leads to a reduction in the total mass and price attributed to air handling units within the HVAC system, due to their lower frequency of replacement compared to other components, including distributing cabinets and cable trays. However, because distributing cabinets have significantly lower Product Circularity

Indicators (PCIs), they exert a stronger influence on both the mass-based (SCI(M)) and economic value-based (SCI(E)) System Circularity Indicators. Additionally, the share of lighting fittings and sanitary fixtures in the total price increases noticeably, resulting in a more pronounced effect on the SCI(M) and SCI(E) outcomes. After accounting for RTs, the SCI(M) decreases by 0.01, while the SCI(E) increases by 0.01, though these changes are relatively minor.

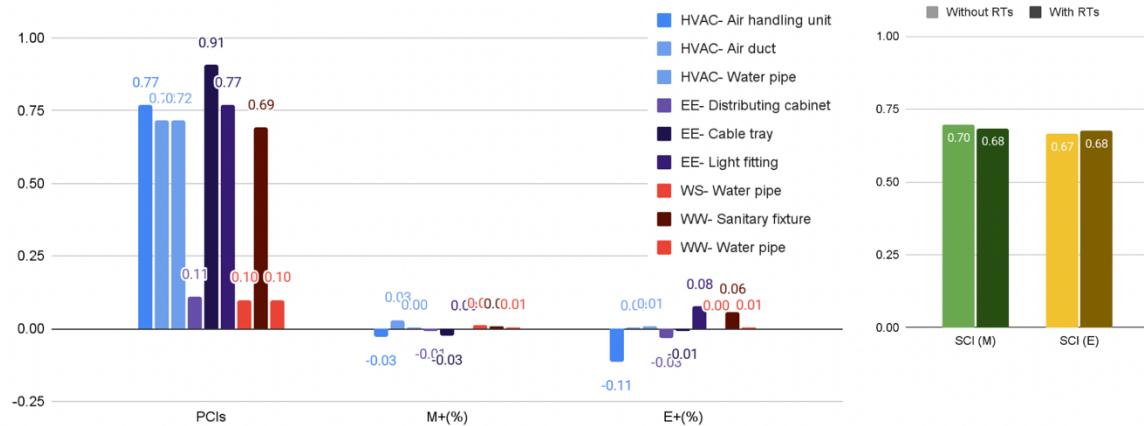


Figure 40. PCIs and increased/decreased proportions in mass and price of building products in service system, and SCI of TCV's service system normalized by total mass and price before and after considering RTs

3.4 Assessment at the Building Level

Before Considering Renovation Times (RTs)

For assessing the circularity of a building, the normalization factor (N) is used to summarize the circularity of different building systems. In this study, both the mass (M) and price (E) of these systems are used for normalization. The different SCI results based on both normalization factors are presented and shown in Figure 41.

The final Building Circularity Indicator (BCI) for the case study is 0.47 when mass (M) is used as the normalization factor (N), but rises significantly to 0.58 when economic value (E) is applied.

This disparity stems from two key factors:

(1) Structural System Impact

- With M as N , the structural system has the lowest SCI (0.40) but the highest mass proportion (63%).
- Switching to E as N , the structural system's SCI increases to 0.47, while its proportion drops to 47%, reducing its negative influence on the overall BCI.



(2) Exterior System Contribution

- Using M as N , the exterior system has the second-highest SCI (0.63) and a 21% mass proportion.
- With E as N , its SCI rises to 0.71, and its proportion grows to 36%, amplifying its positive effect on the final BCI.

These shifts highlight how normalization factor selection—whether prioritizing mass or economic value—directly shapes circularity assessments by altering the relative weight of systems within the building.

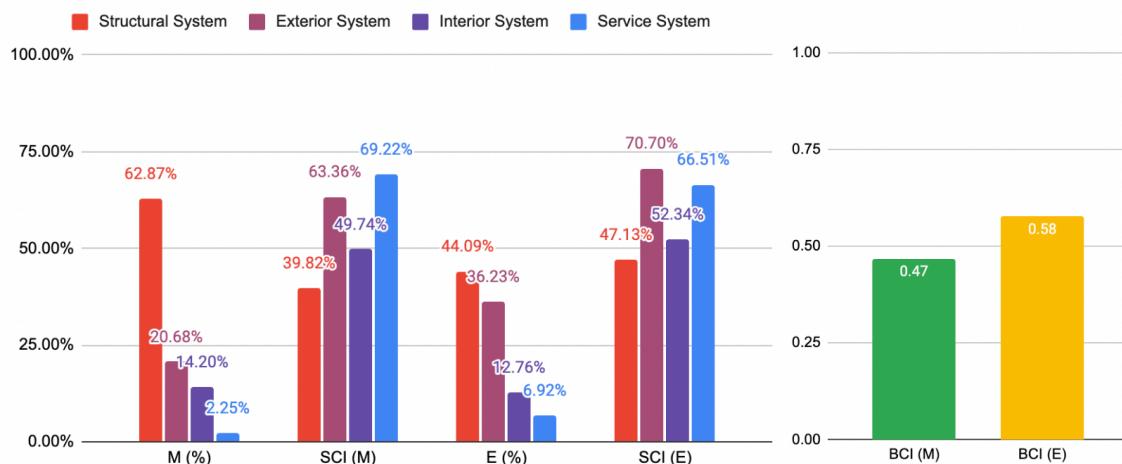


Figure 41. The proportions of different building systems in M and E , before considering RTs and their respective SCI results, normalized by both N factors

After Considering Renovation Times (RTs)

Figures 42 and 43 depict the increases in both total mass (M) and economic value (E) at the procurement stage (i.e., purchase price) for various building systems, taking into account the renovation times (RTs) of different building products across the entire lifecycle (WLC) framework.

In the case study, the total mass rises from 1,355 to 1,885 tons, representing an increase of approximately 39%, while the total economic value grows from 1.2 million to 2 million USD, an increase of about 66%. After factoring in RTs, both the interior and service systems experience significant growth in mass and value. However, despite these increases, the service system's share remains relatively small compared to other systems, resulting in a limited effect on the Building Circularity Indicator (BCI) both before and after accounting for RTs.

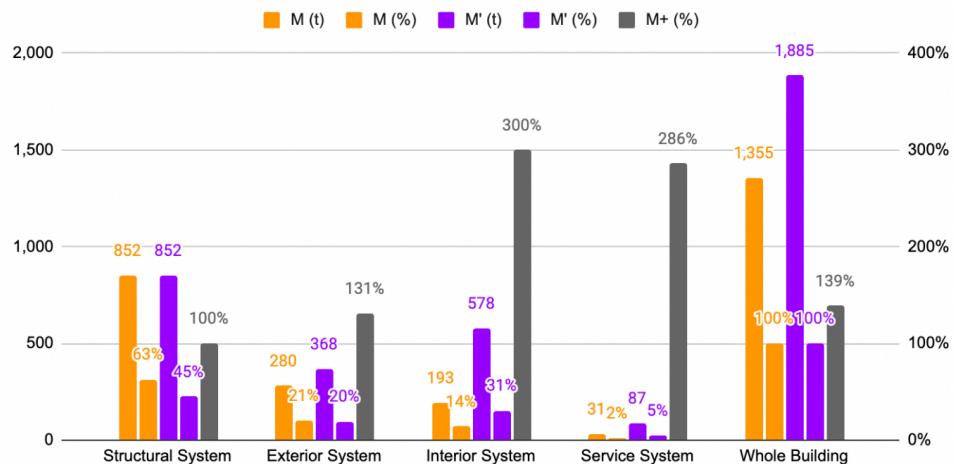


Figure 42. The amount and proportion in M of different building systems before and after considering the factor of RTs

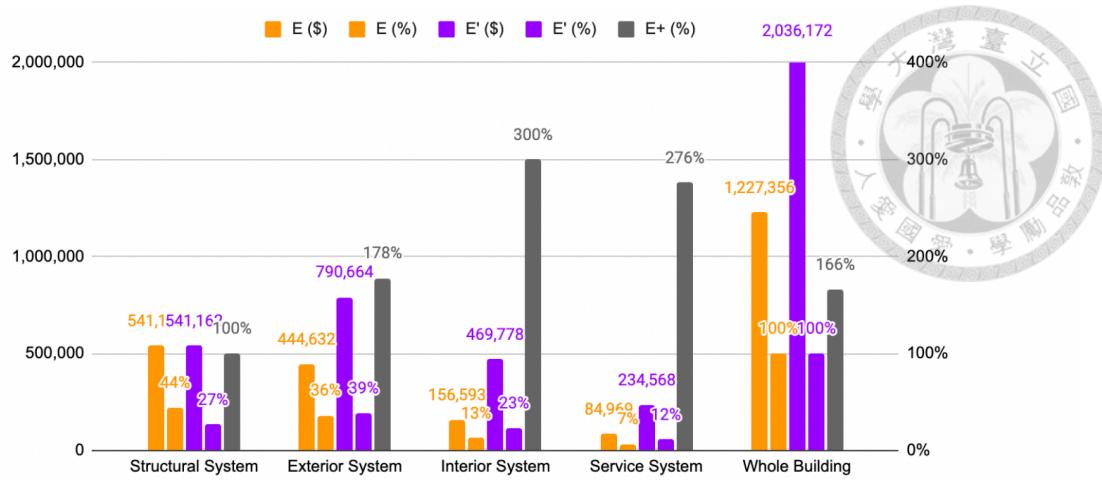


Figure 43. The amount and proportion in E of different building systems before and after considering the factor of RTs

As illustrated in Figure 44, incorporating the renovation times (RTs) factor results in only a minimal change to the BCI, with the value increasing by just 0.02. This limited difference arises because the SCI results for all building systems change by less than 0.03 when the RTs factor is considered. Even though the structural and interior systems undergo notable adjustments after accounting for RTs, their respective SCI results remain unchanged.

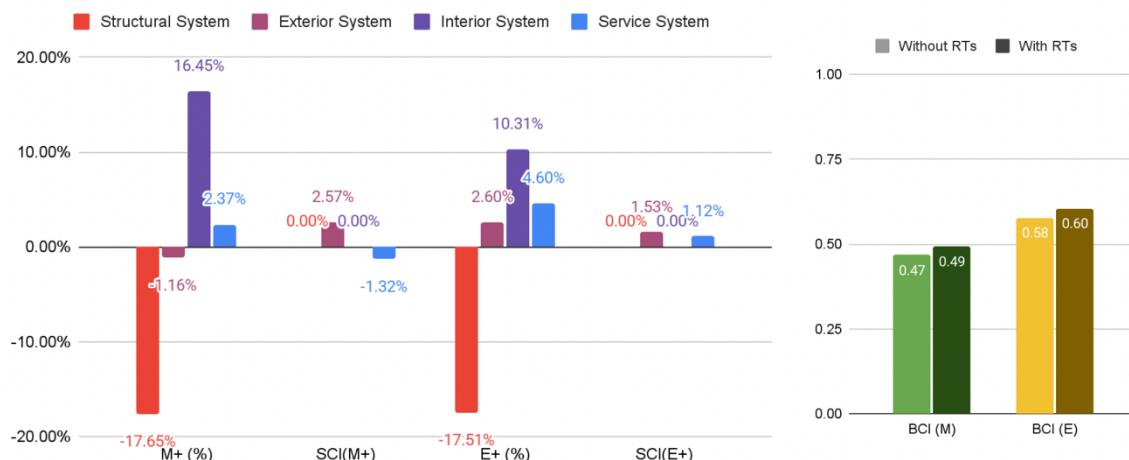


Figure 44. The differences of the proportion in M and E and SCI results normalized by both M and E of different building systems after considering the RTs factor and the associated different BCI results

4. Discussions

4.1 Lessons Learnt from EBCI Assessment



The literature review highlights both the strengths and limitations of the Material Circularity Indicator (MCI) for Building Circularity Assessment (BCA). The key strengths of the MCI are:

(1) Comprehensive Framework:

It provides a clear and structured assessment framework grounded in complete material flow analysis over the entire lifecycle of a product.

(2) Alignment with Circular Economy Principles:

The MCI incorporates essential circular economy strategies, such as closing material loops through the use of renewable resources, component reuse, and material recycling, as well as extending product lifespan and increasing usage intensity.

(3) Clear, Comparable Results:

The MCI expresses circularity performance as a percentage value, making it straightforward to interpret and facilitating easy comparison between different products.

While the strengths of the Material Circularity Indicator (MCI) are widely acknowledged, it also presents several limitations when applied to Building Circularity Assessment (BCA). First, buildings are made up of numerous systems, each with distinct functions and lifespans, which means that the traditional hierarchy of material, product, and building levels should be expanded to include a system level in between. Second, buildings consist of a wide array of products with diverse assembly methods and often lack standardized production processes. As a result, design for disassembly and modular design are especially important in the building sector—more so than in many other industries—yet these critical aspects are currently absent from the MCI framework.

These two shortages have been addressed by various Building Circularity Indicators (BCIs) developed based on MCI. However, several gaps in current assessment frameworks remain: (1) the well-known “reduce” or “narrowing” strategy for a circular economy is not reflected, which is important for the building industry, as it is a major resource consumer worldwide. Thus, the factor of lightweight design should be incorporated into the MCI framework. (2) The adoption of new business models for a circular economy in the building industry is still under exploration. Meanwhile, there is no discussion yet on how to reflect the benefits of these new models within the current MCI framework. (3) The negative effect of downcycling is not yet reflected in the MCI framework, which is very common for the building industry. This factor should be added to MCI for BCA to provide incentives for the industry to develop technology or business models that retain the value of building products.

Besides these three shortcomings of existing MCI-based BCI frameworks, there is one more gap in existing BCI research: past BCI research has used mass as the normalization factor to summarize the circularity of a building across material, building, and system levels. However, some building products and systems have large weights but low economic values—the difference between using mass and economic values as the normalization factor has yet to be discussed.

In this study, various factors are incorporated into the assessment framework to address the shortcomings of existing BCI frameworks. A detailed case study is conducted to evaluate the effectiveness of the proposed framework in filling the remaining research gaps, which are discussed at the four assessment levels that follow.

4.1.1 Assessment at the Material Level

Within the original Material Circularity Indicator (MCI) framework, the primary factors influencing circularity assessment include circular material inputs—such as the fraction of reused

(F_U), recycled (F_R), and renewable (F_S) feedstocks—end-of-life circular loops—encompassing component reuse (C_U), closed-loop recycling (C_R), cascading (C_C), and energy recovery (C_E)—and the utility factor, represented by the ratios of extended lifespan (L/Lav) and usage intensity (U/U_{av}). These elements are retained in this study, with their significance unchanged. For instance, in the structural and interior systems of the current case study, the recycled feedstock fraction (F_R) is pivotal for enhancing MCI outcomes. Utilizing steel sections manufactured via electric furnaces and covering panels sourced from recycled materials (i.e., with elevated F_R values) leads to substantial improvements in the MCI scores of these building products, which in turn positively affect the corresponding System Circularity Indicator (SCI) and Building Circularity Indicator (BCI) results. In the exterior and service systems, the extended lifespan factor (higher L/Lav values) exerts a beneficial influence on MCI results, especially for elements such as roofs, facades, and mechanical, electrical, and plumbing (MEP) equipment in the case study. The advantages of selecting more durable products and implementing innovative business models—such as Product-as-a-Service (PaaS)—are thus effectively captured and reflected in these circularity assessments.

Beyond the established factors derived from the Material Circularity Indicator (MCI) framework, this study incorporates two additional elements—lightweight design (L_w) and recycling level (L_v)—into the material-level circularity assessment. By doing so, the framework now accommodates both the “reduce” principle from the 3Rs and the “narrowing” strategy outlined in the Circular Strategies Navigator (CSN) framework (Geissdoerfer et al., 2018). The benefits of employing lightweight building products, such as precast void reinforced concrete (RC) slabs and dry partition walls, are now quantifiable, enabling reductions in overall material consumption to be directly reflected in the assessment. Moreover, distinguishing between different recycling levels allows the circularity assessment to recognize and reward efforts aimed at

retaining the economic value of products within a circular economy. This approach incentivizes stakeholders in the construction sector to develop and adopt technologies that generate high-value recycled materials, such as premium recycled aggregates for RC elements and windows manufactured from recycled glass.

Although TCV is a pilot project in Taiwan that has adopted many circular approaches, the variety of building materials and products is limited. For example, the use of bio-based materials is relatively limited (e.g., wooden door panels). It is excluded from this study due to its limited total mass and initial price (i.e., less than 1% in the related system). More research is needed to collect information on the MCI of a wider variety of building materials and products in Taiwan through additional case studies.

4.1.2 Assessment at the Product Level

In many existing BCI frameworks based on MCI, the factor of disassembly potential (D_p) is highlighted in the circularity assessment at the product level. The existing assessment methods for D_p are complex, as they address the complex relationships between different building products in various systems. This is also the case in some European countries, where the prefabrication of building components is more common, and their assembly methods are of greater variety. However, in Taiwan, due to the abundant supply of cement and aggregates and the frequent occurrence of earthquakes, grouting and welding are common practices used to join different building components.

This study introduces a simplified approach for evaluating the disassembly potential (D_p) within the context of Taiwan's construction industry. By adapting and applying D_p to the Product Circularity Indicator (PCI), the framework effectively captures the reduced disassembly potential associated with traditional construction methods commonly used in Taiwan. The advantages of

selecting building products with greater ease of disassembly—such as steel sections, drywall, and curtain wall systems—are clearly reflected in the PCI results from our case study. To further refine and validate the parameters established in this research, additional studies are recommended, including a series of case analyses, in-depth interviews with green building experts, and future investigations into the optimal integration of existing Dp assessment methodologies.

Current MCI-based Building Circularity Indicator (BCI) frameworks do not account for modularity, meaning the advantages of modular design—such as reduced construction costs and increased potential for product reuse—are not captured in circularity assessments. To address this gap, this study introduces a modularity factor (Md) into the PCI calculation, along with a simplified evaluation method for Md. This addition allows the contributions of the design team's modular strategies in the case study—applied to structural, exterior, and interior components—to be recognized in the assessment results. However, as with the disassembly factor (Dp), further research is necessary to validate the Md parameters used in this study and to explore the optimal integration of existing Md assessment methodologies.

4.1.3 Assessment at the System & Building Level

In addition to the existing MCI-based BCI frameworks and studies, this study added the factor of renovation times (RTs) following the Whole Lifecycle Analysis (WLCA) framework and the economic value (E) of building products as the normalization factor (N) in comparison with using mass (M) for normalization to have more understanding of the characteristics of different building products and systems. The different SCI and BCI results of our study case with and without these factors are shown in the previous section.

Overall, the System Circularity Indicator (SCI) and Building Circularity Indicator (BCI) results that incorporate renovation times (RTs) are nearly identical to those calculated without this factor.

Given the minimal differences observed and the additional workload required, incorporating RTs into the BCI framework is not advisable. To further substantiate this conclusion, additional research should be conducted to gather data on the lifespans of a broader array of building products in Taiwan, using more case studies to compare SCI and BCI outcomes under different scenarios.

Overall, normalizing by economic value (E) results in higher System Circularity Indicator (SCI) and Building Circularity Indicator (BCI) scores compared to normalization by mass (M). This suggests that many building products and systems with superior circularity are both lighter and more expensive than their conventional counterparts. Using economic value as the normalization factor can incentivize the adoption of products with greater economic worth and higher circularity potential, thereby boosting SCI and BCI outcomes. However, this approach also requires more extensive data collection. To determine which normalization factor is most effective, further research should gather economic value data for a broader range of building products through additional case studies. This research should also include comparative analysis and discussions with green building experts to interpret the implications of different SCI and BCI results.

4.2 Lessons Learnt from TCV's Case Study

4.2.1 TCV's Structural System

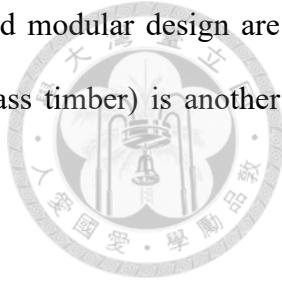
TCV's structural system is a combination of a steel frame and reinforced concrete (RC) slabs. While the circularity performance of steel components is higher than that of RC ones, their mass is smaller, which leads to a lower SCI result when using mass as the normalization factor. To improve the SCI result of this system, three potential strategies are suggested: (1) increasing steel sections' PCI result, (2) increasing RC slabs' PCI result, and (3) reducing the amount of RC components. More discussions are as follows.

The potential for improving the PCI result of steel sections is higher than that of RC slabs in Taiwan. Taiwan is an island country with limited natural resources, particularly in the absence of local metal mines, resulting in a high dependence on metal imports and a high recycling rate of metal materials. This limitation also underscores the need to manufacture steel components using recycled feedstocks for Taiwan's construction industry, as approximately 50% of the steel sections and 70% of the reinforcing bars are produced from recycled sources via electric furnaces. By using steel components made via electric furnaces, the PCI results of these products can increase highly.

Meanwhile, the potential for raising the PCI result of RC components is limited in Taiwan due to the following reasons. The major components of RC are cement and aggregates, accounting for more than 90% of the mass. After the end of the life of RC buildings, it is common to recycle and reuse the waste concrete in other construction projects, as required by local regulations. However, this practice is limited to non-structural components according to the structural design code in Taiwan, which restricts the use of recycled concrete, mostly as aggregate for road infrastructure. Currently, due to the abundant supply of raw aggregate and limestone from Taiwan's rivers and mountains, the economic value of recycled aggregate and cement is relatively low, and the related technologies are quite rare. To overcome these barriers, the public sector in Taiwan should invest in related technologies, modify the existing structural design code, and provide incentives for using recycled aggregate and cement.

For future building projects in Taiwan, utilizing a steel structural system with steel components manufactured via an electric furnace is a good strategy to achieve higher circularity performance, given its higher fraction of recycled feedstocks, modularity, and economic value after the end-of-life stage. Nevertheless, its higher construction cost and carbon footprint should also be aware and considered. In the meantime, if an RC structured project aims to achieve higher circularity, except

by using recycled rebar, cement, and aggregates, durable, lightweight, and modular design are good strategies to consider. Lastly, utilizing bio-based materials (e.g., mass timber) is another viable alternative worth considering and exploring.



4.2.2 TCV's Exterior System

The TCV's exterior system is composed of inclined steel roof panels, precast reinforced concrete (RC) drywalls, and curtain walls made of aluminum frames, panels, and glass windows. The SCI result of this system is high due to the high fraction of recycled feedstocks used in the curtain walls (i.e., the use of recycled aluminum for frames and panels) and its durable design for roofs and drywalls. To improve its SCI results, two potential strategies are suggested: (1) increasing roofs' PCI result by using steel panels made of recycled material, (2) increasing the PCI result of exterior walls with lightweight design, and (3) increasing curtain walls' PCI result by using windows with recycled glass. The latter one is more challenging because there is a trade-off relationship between better insulation and circularity performance of glass: more coating and layers of glass lead to more difficulties for recycling.

For future building projects in Taiwan, utilizing a curtain wall system is a good strategy to achieve a higher circularity of the exterior system, given its higher fraction of recycled feedstock, modularity, and economic value after the end-of-life stage. However, its higher construction cost and carbon footprint should also be aware and considered. Meanwhile, for typical buildings made of RC walls and roofs in Taiwan, precast and dry construction methods, as well as modular and durable design, are key strategies suggested to achieve higher circularity results. Last but not least, using bio-based materials (e.g., mass timber) is also another good alternative worthy of consideration and exploration.

4.2.3 TCV's Interior System

The TCV's interior system is composed of two types of floorings, four types of partition walls, and three types of concealed ceilings. The SCI result of this system is limited because of the lower PCI results and higher proportions in both the mass and price of the dry partition walls. To raise its SCI result, two potential strategies are suggested: (1) increasing the PCI results of the dry partition walls by increasing the fraction of recycled feedstocks for the tiles and panels used, and (2) increasing the PCI results of the floorings by increasing the fraction of recycled feedstocks for the tiles and panels used and adopting durable design.

For future building projects in Taiwan, utilizing a dry partition wall system is a good strategy to achieve a higher circularity of the interior system due to its lightweight feature, higher disassembly potential, and modularity. Nevertheless, covering panels and tiles made of recycled feedstocks need to be used to achieve higher circularity for these building products, and the trade-off relationship between high circularity and cost needs to be aware and considered. Meanwhile, using raised floorings and concealed ceilings are also good circular strategies regarding their higher disassembly potential and modularity.

For typical buildings in Taiwan, which are typically made of reinforced concrete (RC) interior walls and ceramic floorings, modular design and recycled feedstock are two effective strategies to achieve higher circularity, although the improvement is limited. Lastly, utilizing bio-based materials (e.g., wood and bamboo) is another viable alternative worth considering and exploring.

4.2.4 TCV's Service System

The TCV's service system comprises five subsystems: HVAC, electrical engineering (EE), water supply (WS), wastewater (WW), and fire protection (FP) systems. The FP system is not considered in this study because local fire regulations limit its use of circular materials and design.

Among the four assessed subsystems, the HVAC system has the highest circularity performance and proportion in terms of mass and price, playing a critical role in improving the overall SCI result. Meanwhile, the EE system has the second-largest proportion in terms of mass and price. Still, its circularity performance is the second lowest due to the low circularity performance of the distributing cabinets. To improve the SCI result of TCV's service system, two potential strategies are suggested: (1) increasing the EE system's PCI result by increasing distributing cabinets' PCI result, and (2) increasing WW and WS system's PCI results by increasing the PVC water pipes' PCI result. More discussions are as follows.

Distributing cabinets are essential in the EE system, which is composed of numerous cables and switches made of various material types, ranging from metal to plastic. As smart building systems gain popularity nowadays, the importance and complexity of distributing cabinets also grow. However, the reuse and recycling of distributing cabinets are fairly limited in Taiwan and worldwide due to their fast-evolving demands and highly complex composition. Therefore, circular business models for distributing cabinets are highly needed. In the meantime, water pipes are essential in the WS and WW system. They are usually made of PVC in Taiwan because of its low cost, resulting in low circularity performance because of its low economic value after use. Therefore, the government should provide incentives for the recycling of PVC water pipes.

For future building projects in Taiwan, adopting a Product-as-a-service (PaaS) model for their Mechanical, electrical, and plumbing (MEP) equipment is a good strategy to increase the circularity performance of service system because it can raise the reuse and recycle potentials of these products after end-of-life and extend their lifespans by manufacturers and suppliers. In this study, the fraction of reusable components and the factor of lifespan extension are assumed based on suppliers' estimates. More studies are needed to validate the robustness of these models.

Besides adopting the PaaS model, several strategies are suggested to increase the SCI result of the service system. Extending the lifespan of MEP equipment should be highlighted, as their average lifespans are usually limited (e.g., approximately 10 years for lighting fixtures and sanitary fixtures). Increasing their lifespans can effectively reduce their renovation times and material consumption under the WLCA framework. Additionally, avoiding overdesign for HVAC and lighting systems is crucial in reducing material consumption and waste.

4.2.5 TCV's Overall Profile

Among the four different systems in our study case, the exterior and service systems have higher SCI results due to their modular and durable design and PaaS business model, whereas the structural and interior systems have lower SCI results because of their limited use of recycled feedstocks. Further investigations are needed to explore the potential room for improvement and limitations of these different systems.

In the meantime, the structural and exterior systems have a greater impact on the final BCI results, as their proportions in terms of mass and price are larger than those of other systems. This trend is slightly different when considering the RTs of different building products under the WLCA framework: the total mass of the interior system surpasses the exterior, and the total procurement price of the exterior system surpasses the structural cost. Whether the importance of different systems should be determined by their proportion in mass and price requires further investigations via more case studies.

4.3 Comparison with Common Building Project



4.3.1 Assessment of a Common Housing Project

Chang et al. (2024) also used the EBCI framework to evaluate a common housing project in Taiwan (see Figure 45). Its assessment result is shown in Figure 46. The Yangmei Social Housing No.1 (YSH1) project, a representative example of conventional reinforced concrete (RC) construction in Taiwan, demonstrated a relatively low level of building circularity. This reflects the broader challenges that traditional construction methods face when transitioning toward circular economy principles. According to the assessment, the project's overall Building Circularity Index (BCI) was 0.25. This low score was primarily driven by the structural system, which accounted for 71% of the building's total weight and had limited potential for disassembly and reuse.

Yangmei Social Housing No.1



Location: Taoyuan

Structural Type: Reinforced Concrete (RC) Structure

Building Height: 15 floors above ground / 2 floors below ground

Total Floor Area: 33,107.49 square meters

Number of Residential Units: 216

Figure 45. Basic information of another study case- Yangmei Social Housing No.1 (adopted from Chang et al., 2024)

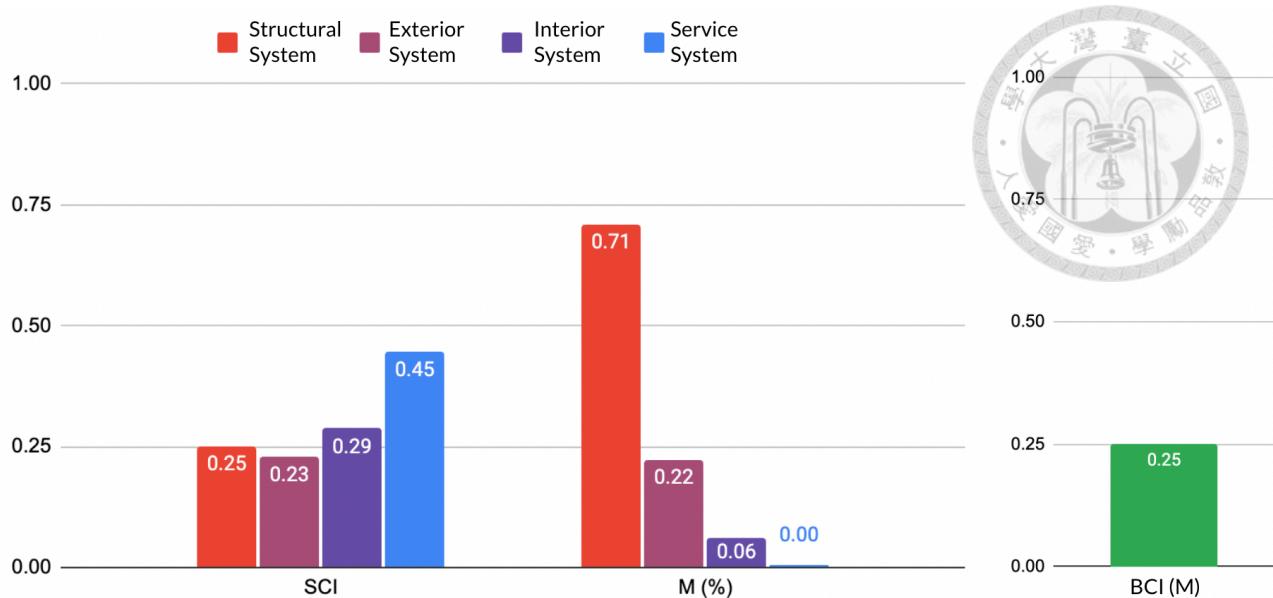


Figure 46. The EBCI assessment result of another study case- Yangmei Social Housing No.1 (adopted from Chang et al., 2024)

System-level evaluations further revealed the limitations of the design. The structural system achieved a System Circular Index (SCI) of 0.25, primarily due to the use of cast-in-place reinforced concrete (RC) and low component modularity. The façade system, constructed with RC walls, ceramic tiles, and standard aluminum windows, scored even lower at 0.23 due to its poor potential for disassembly and material recovery. The interior system, which included wet-built partitions and quartz tile flooring, performed slightly better with an SCI of 0.29, benefiting from a partial degree of removability. Among all systems, the equipment system performed best, achieving an SCI of 0.45. This was attributed to the high recyclability of metal-based components, although its performance could be enhanced through the adoption of leasing models or service-based strategies.

A key observation was that the structural system's dominance in building weight heavily influenced the overall circularity outcome. The limited use of modular construction and dry assembly methods in both the façade and interior systems further reduced the potential for material

recovery and reuse. While the equipment system showed promise, its benefits were constrained by the lack of product-as-a-service (PaaS) implementation. Additionally, the impact of system replacement frequency (RTs) was minimal in this project, reinforcing the idea that material selection and component design are still the most critical factors in achieving higher circularity.

To improve future performance, it is recommended that public housing projects prioritize the use of modular, demountable, and lightweight structures. The implementation of dry construction methods and easily replaceable interior finishes should also be considered. Moreover, equipment systems should transition toward leasing and maintenance-oriented models to enhance lifecycle efficiency. Finally, integrating circular economy thinking during the early stages of project planning and design is essential. These strategies will help future public buildings achieve higher circularity and reduce their environmental impact in line with the Sustainable Development Goals.

4.3.2 Assessment between TCV and YSH1

Figure 47 presents a detailed comparison of building circularity between Taisugar Circular Village (TCV) and Yangmei Social Housing No. 1 (YSH1), examining four key building systems: structural, exterior, interior, and service. The evaluation covers system-level contributions in terms of mass proportion (M%), economic value proportion (E%), and system circularity indicator (SCI), with final Building Circular Index (BCI) scores presented for both weight-based (M) and economic value-based (E) normalization methods.

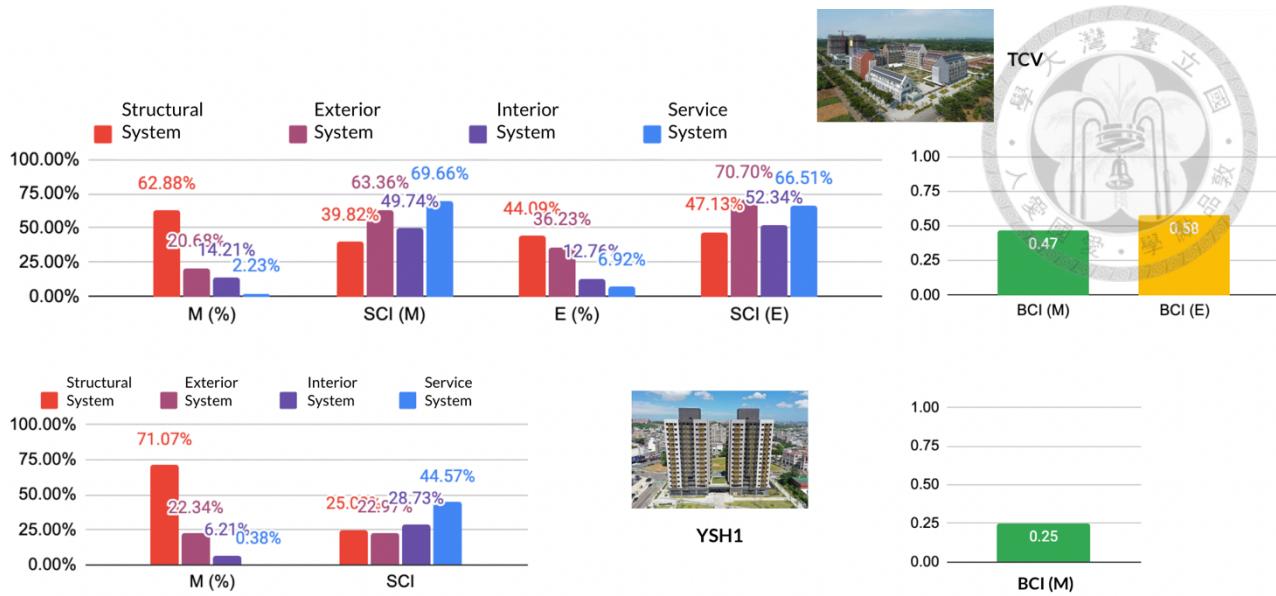


Figure 47. Comparison between the ECBI assessment results of two study cases- TCV and YSH1 (adopted from Chang et al., 2024)

Overall, TCV demonstrates a significantly stronger circular performance than YSH1. TCV achieved a BCI of 0.47 based on material weight and 0.58 based on economic value. In contrast, YSH1 recorded a much lower BCI of 0.25 (M). The differences between the two projects stem from several core factors.

Most notably, TCV incorporated a comprehensive range of circular design strategies, including prefabricated components, modular layouts, reversible construction, lightweight structural systems, and product-as-a-service models. These strategies significantly enhanced the building's capacity for disassembly, reuse, and adaptability. In contrast, YSH1 adopted a conventional in-situ RC approach paired with traditional finishes and materials. This led to limited modularity, poor disassemblability, and, ultimately, lower circularity across its systems.

Material selection and construction techniques also played a critical role in circular performance. TCV used structural steel and precast hollow-core slabs, which are inherently more

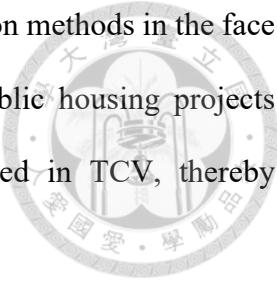
circular due to their higher recyclability and modular nature. Its façade featured modular aluminum curtain wall systems designed for reusability. Conversely, YSH1 relied heavily on cast-in-place concrete, ceramic tiles, and quartz bricks, which were installed using wet trades. These materials and methods limit the potential for future recovery, reuse, or upgrading, thereby reducing the overall system's flexibility and lifespan.

A closer look at the system-level breakdown further reinforces these observations. In terms of material distribution, TCV's structural system accounted for 62.88% of the building's weight, while YSH1's structural system made up an even greater share at 71.07%. The dominance of structural materials in both cases significantly influenced the BCI, particularly since the structural system is often the most difficult to disassemble or adapt. TCV's use of prefabricated and lightweight structural elements proved crucial in mitigating this limitation, boosting its overall circularity.

SCI values also highlight the performance gap. TCV exhibited high SCI scores across all systems when normalized by weight—69.66% for service, 63.36% for exterior, 49.74% for interior, and 39.82% for structural components. In contrast, YSH1's systems were notably weaker, with SCI values ranging from 22.34% (exterior) to 44.57% (service) and only 25.02% for the structural system. These low scores reflect the project's minimal adoption of modular construction, limited reusability of materials, and overall lower design flexibility.

In conclusion, TCV significantly outperforms YSH1 in all aspects of building circularity. Its success is attributed to the early integration of circular economy principles, including prefabrication, modularity, reversible design, and service-oriented models. These strategies collectively enhance the building's long-term resilience, sustainability, and potential for reuse.

YSH1, on the other hand, reflects the limitations of conventional construction methods in the face of growing environmental and resource efficiency challenges. Future public housing projects would greatly benefit from adopting the circular strategies demonstrated in TCV, thereby advancing both environmental performance and long-term value.



4.4 Comparison with Existing Green Building Assessment Systems

Lin (2019) developed a framework for circular building design strategies in Taiwan. The framework consists of three levels: three-stage goals, seven circular design strategies, and four building layers with different lifespans (see Figure 48). After establishing the framework, the study compared it with the existing Taiwanese Green Building Evaluation System (i.e., EEWH) to identify the missing circular design strategies in domestic green buildings (see Table 3). By filling in the EEWH indicators related to material circulation into the table corresponding to the seven circular strategies and four building layers, it was found that the current EEWH lacks the concept of reusing building materials during the demolition phase. Additionally, using old components and designing for spatial flexibility are also strategies not specified by EEWH. EBCI can address these gaps.

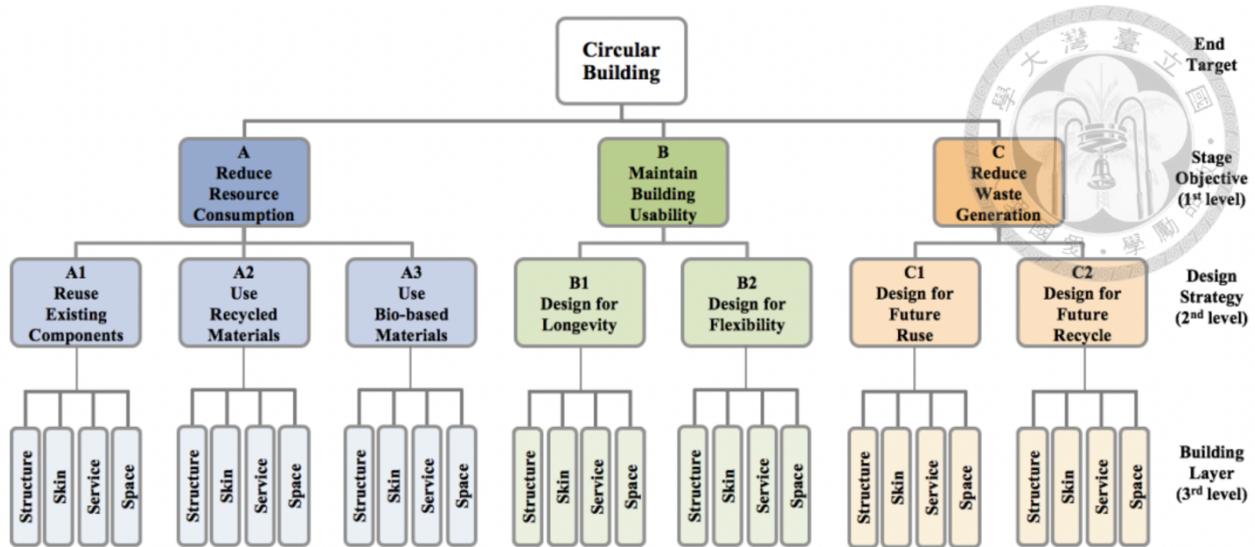
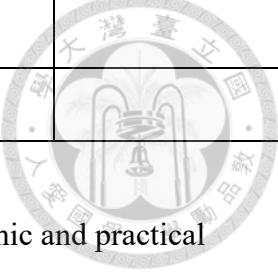


Figure 48. A conceptual framework for circular building design strategies in Taiwan (adopted from Lin, 2019)

Table 3. The design strategies related to circular buildings in Taiwan's Green Building Evaluation System (adopted from Lin, 2019)

Circular Building Strategy	Structure	Skin	Service	Space
A1. Reuse Existing Components	<ul style="list-style-type: none"> • CO₂ reduction indicator • Waste reduction indicator 			
A2. Use Recycled Materials	<ul style="list-style-type: none"> • CO₂ reduction indicator (use of recycled materials) • Waste reduction indicator (reducing demolition waste) 			<ul style="list-style-type: none"> • CO₂ reduction indicator • Waste reduction indicator • IEQ indicator (green building materials)
A3. Use Bio-based Materials	<ul style="list-style-type: none"> • CO₂ reduction indicator (lightweight construction) • Waste reduction indicator 			<ul style="list-style-type: none"> • IEQ indicator (green building materials)
B1. Design for Longevity	<ul style="list-style-type: none"> • CO₂ reduction indicator (durability) 		<ul style="list-style-type: none"> • CO₂ reduction indicator (durability) 	
B2. Design for Flexibility				

C1. Design for Future Reuse				
C2. Design for Future Recycle				

To ensure the EBCI framework contributes meaningfully to both academic and practical domains, several promotion strategies are recommended:

(1) Integration into Public Procurement and Building Standards

Collaborate with government agencies and standards bodies to integrate EBCI into green building certification systems, such as EEWH (Taiwan). Establishing EBCI as part of procurement criteria or building permit requirements will incentivize its use in public and private sector projects.

(2) Policy Advocacy and Incentive Programs

Advocate for policy incentives such as tax reductions for projects that meet high EBCI scores. Linking circularity assessment to economic incentives can accelerate market adoption.

(3) Partnerships with Industry Stakeholders

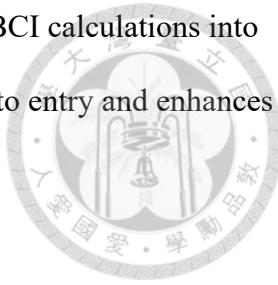
Forge partnerships with construction firms, architectural practices, and real estate developers to pilot EBCI in diverse building typologies. Early involvement with practitioners will provide valuable feedback for further refinement and increase buy-in from industry players.

(4) Incorporation into Academic Curricula and Professional Training

Introduce EBCI into university courses related to sustainable architecture, construction management, and civil engineering. Additionally, it offers workshops and certification programs for professionals to increase awareness and competency in applying EBCI.

(5) Open-Source Digital Tools and BIM Integration

Develop an open-source digital platform or plugin that integrates EBCI calculations into popular BIM software (e.g., Autodesk Revit). This reduces barriers to entry and enhances usability in real-world design and documentation processes.



5. Conclusion



A circular economy is an innovative model that promotes the closure of material loops and the preservation of product values throughout their lifecycles, leading to reduced natural resource consumption and lower environmental pollution. As a major consumer and polluter, how the building industry can transform into a circular and sustainable one is an urgent question to be answered. Besides identifying the key approaches and strategies to achieve higher building circularity, determining how to measure and assess their effectiveness is another important research area. Among the existing building circularity assessment methods, the material flow analysis (MFA)- based method, named the Material Circularity Indicator (MCI), has garnered the most attention and adoption. Nevertheless, MCI was originally developed for a common industry product, which differs from building as a product since it's commonly unique and complex. A systematic discussion on how MCI can be applied to build circularity assessment is lacking.

To address the existing research gap, this study conducted an extensive literature review covering key approaches and strategies for building circularity, current building circularity assessment methods, the Material Circularity Indicator (MCI), and MCI-based Building Circularity Indicators (BCIs). The review identified both the strengths and limitations of the MCI and its derivatives in assessing building circularity. In response to these limitations, this study proposes an Enhanced Building Circularity Indicator (EBCI), which incorporates additional factors such as modular and lightweight design, recycling level, and the principles of whole-building lifecycle assessment into the evaluation framework.

To assess the effectiveness of the proposed framework, a comprehensive case study was undertaken, focusing on a pioneering circular building project in Taiwan that implemented a range of strategies to enhance building circularity. This case study illustrates how the Enhanced Building

Circularity Indicator (EBCI) captures the impact of these strategies at the material, product, system, and building scales, including the adoption of innovative circular economy models such as product-as-a-service. The analysis also examines the influence of different normalization factors—specifically, product mass and initial economic value—as well as the role of renovation frequency within the whole building lifecycle framework, on the overall assessment outcomes. Finally, the findings are used to identify key lessons from the case, highlighting which approaches are most effective in advancing building circularity.

Key highlights of this study include:

(1) Comprehensive Review of Circularity Assessment Tools

This study offers a thorough review and comparison of the Material Circularity Indicator (MCI) and current MCI-based Building Circularity Indicators (BCIs), providing readers with a clear understanding of the strengths and limitations of existing tools for assessing building circularity.

(2) Introduction of the Enhanced Building Circularity Indicator (EBCI) Framework

By introducing the EBCI framework, the study addresses several notable gaps in current assessment methods, particularly by incorporating the modularity and lightweight design factors. These aspects, frequently emphasized in circular building research, are not adequately covered in existing tools, and their inclusion helps to overcome key limitations in present assessment practices.

(3) Detailed Case Study as a Reference for Data Collection and Processing

The in-depth case study presented in this research demonstrates a robust approach to data collection and processing for building circularity assessment. While most prior studies focus on the structural, exterior, and interior systems of buildings, this work

provides valuable guidance on evaluating building service systems—especially within the context of innovative circular business models—making it a useful reference for practitioners and researchers alike.



(4) Comparison of Normalization Factors in Circularity Assessment

Responding to the need highlighted by Khadim et al. (2022), this study compares the impact of using mass versus initial economic value as normalization factors in circularity assessments. By illustrating how assessment outcomes differ depending on the chosen factor, the study offers practical insights to help readers determine which normalization approach best suits their specific evaluation needs.

Several limitations of this study should be acknowledged:

(1) Scope of Case Study:

This research focuses on an in-depth analysis of a pilot circular housing project in Taiwan. While the project incorporates a range of circularity strategies, some practices—such as the use of additional bio-based materials or the adoption of shared business models for space and services—were not implemented and, therefore, not assessed. Expanding the research to include more diverse case studies of circular building projects is recommended.

(2) Variation Across Building Types:

Different building types have unique requirements and compositions, which can influence the effectiveness of various circular strategies. Further investigation through case studies of buildings with different functions is necessary to understand these variations.

(3) Exclusion of Building Landscape:

The building landscape was not included in the assessment due to limited data availability, as the study was confined to the D-house on site. Future research should aim to evaluate this aspect.



(4) Validation of Coefficients:

The appropriateness of the coefficients proposed in this study requires further validation through additional case studies and expert interviews, which are planned for future research.

(5) Simplified Assessment of Disassembly and Modularity:

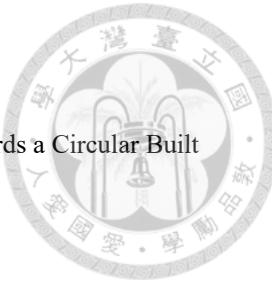
The evaluation of disassembly potential and modularity was simplified for this preliminary study. Further research is needed to develop a more robust and context-appropriate assessment method for Taiwan's building industry.

(6) Comparison with Other MCI-Based BCIs:

A comparative analysis of assessment results using different MCI-based Building Circularity Indicators is suggested. However, challenges in accessing comprehensive data for various factors may limit such comparisons.

Addressing these limitations in future studies will help to strengthen the applicability and reliability of building circularity assessments.

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Appendix

Table A1. Parameters used for calculating MCI of building products in structural system.

Steps	V		W						LFI		X		MCI		
Factors	F _U	F _R	F _S	C _U	C _R	C _C	C _E	E _F	E _C	L _v	L _w	L/Lav	U/Uav	MCI	MCip
Usual RC slab- not including the factor of recycling level (Lv)														0.46	
concrete	0.00	<u>0.05</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	1.00	0.43	93%
steel bar	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	1.00	0.82	7%
Usual RC slab- including the factor of recycling level (Lv)														0.33	
concrete	0.00	<u>0.05</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	<u>0.80</u>	1.00	1.00	1.00	0.29	93%
steel bar	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	1.00	0.82	7%
TCV's RC slab- including the factor of recycling level (Lv) and lightweight design (Lw)														0.39	
concrete	0.00	<u>0.05</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	<u>0.80</u>	<u>0.90</u>	1.00	1.00	0.36	93%
steel bar	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	<u>0.90</u>	1.00	1.00	0.84	7%
TCV's steel frame- using steel generated via a blast furnace														0.47	
steel section	0.00	<u>0.00</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	1.00	0.47	100%
Recycled steel frame- using steel generated via an electric furnace														0.82	
steel section	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	1.00	0.82	100%

The underline indicates the key parameters used in the calculation process, while the bold font highlights the key differences between different calculation scenarios.

Table A2. Parameters used for calculating MCI of building products in the exterior system.

Steps	V		W						LFI		X		MCI			
Factors	F _U	F _R	F _S	C _U	C _R	C _C	C _E	E _F	E _C	L _v	L _w	L/Lav	U/Uav	MCI	%	MCip
Pitched roof- including the factor of extended lifespan (L/Lav)														0.65		
steel panel	0.00	<u>0.00</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	<u>1.50</u>	1.00	0.65	100%	
Drywall- including the factor of extended lifespan (L/Lav) and recycling level (Lv)														0.66		
ceramic tile	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	<u>2.00</u>	1.00	0.70	6%	
mortar	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	<u>0.80</u>	1.00	<u>2.00</u>	1.00	0.63	5%	
concrete	0.00	<u>0.05</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	<u>0.80</u>	1.00	<u>2.00</u>	1.00	0.65	83%	
steel bar	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	<u>2.00</u>	1.00	0.91	6%	
Curtain wall (aluminum frame)														0.82		
alum frame	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	1.00	0.82	100%	
Curtain wall (dormant window)- including the factor of recycling level (Lv)														0.44		
double glass	0.00	<u>0.00</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	<u>0.80</u>	1.00	1.00	1.00	0.34	79%	
alum frame	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	1.00	0.82	21%	
Curtain wall (common window)- including the factor of recycling level (Lv)														0.55		

clear glass	0.00	0.20	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	0.80	1.00	1.00	1.00	0.45	73%
alum frame	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	0.82	27%	
Curtain wall (common window & aluminum panel)- including the factor of recycling level (Lv)															
clear glass	0.00	0.20	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	0.80	1.00	1.00	1.00	0.45	18%
alum part	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	<u>0.90</u>	<u>0.90</u>	1.00	1.00	1.00	0.82	82%	

The underline indicates the key parameters used in the calculation process, while the bold font highlights the key differences between different calculation scenarios.

Table A3. Parameters used for calculating MCI of building products in the interior system.

Steps	V				W				LFI		X		MCI			
Factors	F _U	F _R	F _S	C _U	C _R	C _C	C _E	E _F	E _C	Lv	Lw	L/Lav	U/Uav	MCI	%	MCIp
Ceramic flooring																0.34
ceramic tile	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.41	55%	
mortar	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	0.80	1.00	1.00	1.00	0.26	45%	
Raised flooring																0.47
PVC board	0.00	<u>0.00</u>	0.00	0.00	0.10	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.14	35%	
GS channel	0.00	<u>0.40</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.65	65%	
Dry partition wall (double layers with rockwool) - including the factor of lightweight design (Lw)																0.42
gypsum board	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	0.80	<u>0.09</u>	1.00	1.00	0.34	43%	
cement board	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.47	30%	
rockwool	0.00	<u>0.00</u>	0.00	0.00	0.00	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.19	14%	
iron channel	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.84	13%	
Dry partition wall (single layer with rockwool) - including the factor of lightweight design (Lw)																0.49
cement board	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.47	53%	
rockwool	0.00	<u>0.00</u>	0.00	0.00	0.00	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.19	24%	
iron channel	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.84	23%	
Dry partition wall (single layer without rockwool) - including the factor of lightweight design (Lw)																0.58
cement board	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.47	70%	
iron channel	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.84	30%	
Dry partition wall (double layers without rockwool) - including the factor of lightweight design (Lw)																0.47
crystal tile	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	0.80	<u>0.09</u>	1.00	1.00	0.34	44%	
cement board	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.47	39%	
iron channel	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.84	17%	
Concealed ceiling (expanded metal mesh)																0.82
iron part	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	<u>0.09</u>	1.00	1.00	0.82	100%	

Concealed ceiling (calcium silicate board)	0.00	0.50	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.63	0.71
iron channel	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.82	0.59%
Concealed ceiling (wood cement board)															
WC board	0.00	<u>0.00</u>	0.00	0.00	<u>0.75</u>	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.41	0.67
iron channel	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.82	0.36%

The underline indicates the key parameters used in the calculation process, while the bold font highlights the key differences between different calculation scenarios.

Table A4. Parameters used for calculating MCI of building products in the service system.

Steps	V		W						LFI		X		MCI			
Factors	F _U	F _R	F _S	C _U	C _R	C _C	C _E	E _F	E _C	L _v	L _w	L/Lav	U/Uav	MCI	%	MCI _p
HVAC system																
Air handling unit- Product as a Service (PaaS) model																
complex entity	0.00	0.00	0.00	<u>1.00</u>	0.00	0.00	0.00	0.90	0.90	1.00	1.00	<u>1.50</u>	1.00	0.70	100%	
Air duct																
GI panel	0.00	<u>0.40</u>	0.00	0.00	0.00	<u>0.90</u>	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.65	100%	
Water pipe																
GS pipe	0.00	<u>0.40</u>	0.00	0.00	0.00	<u>0.90</u>	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.65	100%	
Electrical engineering (EE)																
Distributing cabinet																
complex entity	0.00	0.00	0.00	<u>0.00</u>	0.00	0.00	0.00	0.90	0.90	1.00	1.00	<u>1.00</u>	1.00	0.10	100%	
Cable tray																
aluminum bar	0.00	<u>0.80</u>	0.00	0.00	<u>0.90</u>	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.82	100%	
Light fitting- Product as a Service (PaaS) model																
complex entity	0.00	0.00	0.00	<u>1.00</u>	0.00	0.00	0.00	0.90	0.90	1.00	1.00	<u>1.50</u>	1.00	0.70	100%	
Water supply (WS) engineering																
Water pipe																
PVC pipe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.10	100%	
Wastewater (WW) engineering																
Sanitary fixture- Product as a Service (PaaS) model																
complex entity	0.00	0.00	0.00	<u>1.00</u>	0.00	0.00	0.00	0.90	0.90	1.00	1.00	<u>1.50</u>	1.00	0.70	100%	
Water pipe																
PVC pipe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.90	1.00	1.00	1.00	1.00	0.10	100%	

The underline indicates the key parameters used in the calculation process, while the bold font highlights the key differences between different calculation scenarios.

Table A5. Parameters used for calculating PCI of building products in the structural system.

Product	MCIp	Assembly at the product level			Modularity at the product level			Assembly at the system level		
		description	Dp	PCI	description	Md	PCI'	description	Ds	PCIs
Usual RC slab	0.33	with cement	0.8	0.26	site cast	1	0.26	with cement	0.9	0.24
Precast RC slab	0.33	with cement	0.8	0.26	precast	1.1	0.29	with cement	1	0.29
TCV's RC slab	0.39	with cement	0.8	0.32	precast	1.1	0.35	with bolt	1	0.35
Usual S frame	0.47	no joint	1	0.47	prefab	1.1	0.52	via welding	0.9	0.47
TCV's S frame	0.47	no joint	1	0.47	prefab	1.1	0.52	with bolt	1	0.52

Table A6. Parameters used for calculating PCI of building products in the exterior system.

Product	MCIp	Assembly at the product level			Modularity at the product level			Assembly at the system level		
		description	Dp	PCI	description	Md	PCI'	description	Ds	PCIs
Drywall	0.66	with cement	0.8	0.53	precast	1.1	0.58	with bolt	1	0.58
Pitched roof	0.65	with bolt	1	0.65	prefab	1.1	0.71	with bolt	1	0.71
CW (AF)	0.82	with bolt	1	0.82	prefab	1.1	0.91	with bolt	1	0.91
CW (DW)	0.44	with rubber	1	0.44	prefab	1.1	0.49	with bolt	1	0.49
CW (CW)	0.55	with rubber	1	0.55	prefab	1.1	0.61	with bolt	1	0.61
CW (CW+AP)	0.76	with bolt	1	0.76	prefab	1.1	0.84	with bolt	1	0.84

Table A7. Parameters used for calculating PCI of building products in the interior system.

Product	MCIp	Assembly at the product level			Modularity at the product level			Assembly at the system level		
		description	Dp	PCI	description	Md	PCI'	description	Ds	PCIs
Ceramic floor	0.34	with cement	0.8	0.27	site cut	1	0.27	with cement	0.9	0.25
Raised floor	0.47	with bolt	1	0.47	prefab	1.1	0.52	with bolt	1	0.52
DPW (DL+RW)	0.42	with bolt	1	0.42	prefab	1.1	0.46	with bolt	1	0.46
DPW (SL+RW)	0.49	with bolt	1	0.49	prefab	1.1	0.54	with bolt	1	0.54
DPW (SL-RW)	0.58	with bolt	1	0.58	prefab	1.1	0.64	with bolt	1	0.64
DPW (DL-RW)	0.47	with cement	0.8	0.38	prefab	1.1	0.42	with bolt	1	0.42
CC (MM)	0.82	with bolt	1	0.82	prefab	1.1	0.91	with bolt	1	0.91
CC (CS)	0.71	with bolt	1	0.71	prefab	1.1	0.78	with bolt	1	0.78
CC (WC)	0.67	with bolt	1	0.67	prefab	1.1	0.74	with bolt	1	0.74

Table A8. Parameters used for calculating PCI of building products in the service system.

Product	MCIp	Assembly at the product level			Modularity at the product level			Assembly at the system level		
		description	Dp	PCI	description	Md	PCI'	description	Ds	PCIs
HVAC-AHU	0.70	with bolt	1	0.70	prefab	1.1	0.77	with bolt	1	0.77
HVAC-AD	0.65	with bolt	1	0.65	prefab	1.1	0.72	with bolt	1	0.72
HVAC-WP	0.65	with casing	1	0.65	prefab	1.1	0.72	with bolt	1	0.72
EE-DC	0.10	with bolt	1	0.10	prefab	1.1	0.11	with bolt	1	0.11
EE-CT	0.82	with bolt	1	0.82	prefab	1.1	0.91	with bolt	1	0.91
EE-LF	0.70	with bolt	1	0.70	prefab	1.1	0.77	with bolt	1	0.77
WS-WP	0.10	with casing	1	0.10	site cut	1	0.10	with bolt	1	0.10
WW-SF	0.70	with casing	1	0.70	prefab	1.1	0.77	with cement	0.9	0.68
WW-WP	0.10	with casing	1	0.10	site cut	1	0.10	with bolt	1	0.10