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Towards Circular Buildings in Hong Kong: A New Integrated Technology–Material–Design (TMD) Circularity Assessment Framework

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Abstract: As Hong Kong faces increasing pressure on resources and environmental sustainability, there is a growing need to shift towards circular building practices. The ever-increasing demand for sustainable urban development necessitates innovative approaches towards greener and more sustainable building design and construction. This paper introduces a new integrated Technology–Material–Design (TMD) Circularity Assessment Framework, a three-dimensional and comprehensive tool designed to evaluate and enhance the circularity level of buildings in Hong Kong. Through an extensive literature review, the research study identifies a new perspective with key metrics and best practices that inform the new assessment framework, enabling various key stakeholders to pinpoint effective strategies for overcoming profound challenges and seizing timely opportunities to foster a more sustainable and resilient built environment. This paper successfully categorises all circularity assessment frameworks into three perspectives, i.e., material-based, technology-oriented, and design-supported. Future research could apply BIM technology to automate and circularise the new assessment framework. Another significant contribution of this paper is the derivation of a new formula for the Building Circularity Index (BCI) for Hong Kong, which quantifies building circularity levels using a set of defined measurement metrics. By providing a robust assessment method, the TMD Circularity Assessment Framework facilitates informed decision making for architects, engineers, governments, developers, policymakers, and other stakeholders in a new horizon. The review findings underscore the potential of the TMD Framework to guide the transition towards more circular buildings, ultimately contributing to the broader goals of environmental sustainability and resource efficiency in Hong Kong's construction and real estate sector.

Keywords: circular economy; circularity assessment; circular design; circular building practices; waste management; material footprint; circularity indicators

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1. Introduction

The adoption of circular economy principles in the Hong Kong built environment is essential for mitigating environmental impact and promoting sustainable development. However, circularity assessment has not been seriously studied and promoted in Hong Kong for the successful implementation of circular building practices. This research aims to develop a new and comprehensive circularity assessment framework for HK's built environment. With this assessment framework to evaluate material recyclability, energy efficiency, waste management, and monitoring mechanisms, stakeholders could help understand and manage the progress and pace towards a closed-loop system. According to the Denmark Circularity Gap Report, Denmark could only achieve 4% circular after years of effort. This unsatisfactory figure brings attention to Hong Kong and provides lessons to improve its course toward a circular economy [1]. Hong Kong's burgeoning population and rapid urbanisation have placed unprecedented pressure on cities to address resource scarcity, waste generation, and environmental degradation. In this context, the circularity concept, which emphasises optimising resource use, reducing waste, and closing material loops [2], offers a compelling framework for addressing these challenges and fostering a more sustainable environment.

Technology such as artificial intelligence could close the existing circularity gap in the building construction industry [3]. By using artificial intelligence, previous research showed that the predicted recyclability of case slabs based on design could be enhanced [4]. Oluleye et al. [5] revealed that data-driven technologies and circularity plans have significant impacts on successful CE implementation. Recent research calls for further development of these tools in terms of interoperability aspects, integration of more sources of data for LCA and circularity, and possibilities for a comprehensive evaluation of design choices [6,7]. Computational plugins offer greater flexibility, while BIM-LCA integrations have the potential to replace dedicated LCA software and spreadsheets.

Additionally, the study identifies opportunities for novel digital methods, such as algorithms for circular design with various types of reused building elements and the sharing of digital twins and material passports. This research can inform future studies and support architects and engineers in their efforts to create a sustainable built environment. The design of BIM with algorithms could make the assessment framework circular and automatic by itself.

A simple keyword analysis in previous works (Table 1) reveals that the transition to circular buildings relies on the interplay between technology, design, and materials to enhance sustainability in the built environment. Innovative design strategies prioritise resource efficiency and adaptability, with guidelines emphasising low-impact biomaterials and extended structural lifespans to enable multiple use cycles [8]. Technology, particularly Building Information Modelling (BIM), plays a key role in optimising material usage, waste reduction, and sustainability throughout the construction process [9]. Additionally, advancements in lightweight structure design support efficient material use, dismantling, and recycling [10]. Material selection is crucial, as circular construction emphasises renewable and recyclable resources while integrating materials, water, and waste management into the lifecycle of buildings [11]. Ultimately, leveraging advanced technologies and design strategies is essential for transitioning to a sustainable, circular construction model that addresses pressing environmental challenges.

This research paper seeks to comprehensively examine the circularity assessment frameworks, with a specific focus on creating an innovative framework for advanced evaluations. It introduces the TMD Circularity Assessment Framework, an innovative tool designed to evaluate and enhance the circularity of buildings in Hong Kong. The framework is developed through an extensive literature review, refining key metrics and best practices from existing circular economy research and applications in the built environment. By providing a structured approach to assess circularity, the TMD Framework enables stakeholders, including architects, developers, and policymakers, to identify strategies for overcoming challenges and capitalising on opportunities for fostering a more sustainable and resilient built environment. The Building Circularity Index (BCI) is firstly derived from the framework for the Hong Kong built environment. The new framework provides a clear and actionable measure of how well a building or a city adheres to circular economy principles, facilitating informed decision making and benchmarking against best practices. The application of the TMD Framework and BCI aims to guide the transition towards circular buildings, ultimately contributing to the broader goals of environmental sustainability and resource efficiency in Hong Kong's construction sector.

Table 1. Analysis of keyword statistics.

Keywords Trend for Circular Building, Technology, Material, and Design			
Keywords	**Number of Documents in Scopus**	**Number of Documents in Web of Science (Keyword Plus)**	**Number of Documents in Google Scholar (Review Articles)**
"Circular Building" AND "Technology"	36	4	356
"Circular Building" AND "Material"	148	15	382
"Circular Building" AND "Design"	158	19	430
"Circular Building" AND "Technology" AND "Material" AND "Design"	14	0	307

This paper is structured as follows (Figure 1): after the introduction, we review the literature on different circularity assessment frameworks. We then describe the development of the TMD Circularity Assessment Framework, detailing the key metrics and best practices identified. Following this, we present the methodology for calculating the Building Circularity Index and discuss its implications for stakeholders. Finally, we conclude with recommendations for future research and practice in circular building design and construction in Hong Kong. This research paper has three objectives. The first is to comprehensively review the existing assessment framework barriers to building circularity in Hong Kong. The second objective is to develop a new assessment framework to calculate the building and zone circularity index to create the Hong Kong Circularity Index for the built environment. The last objective is to draw strategies for enhancing Hong Kong's circularity development.

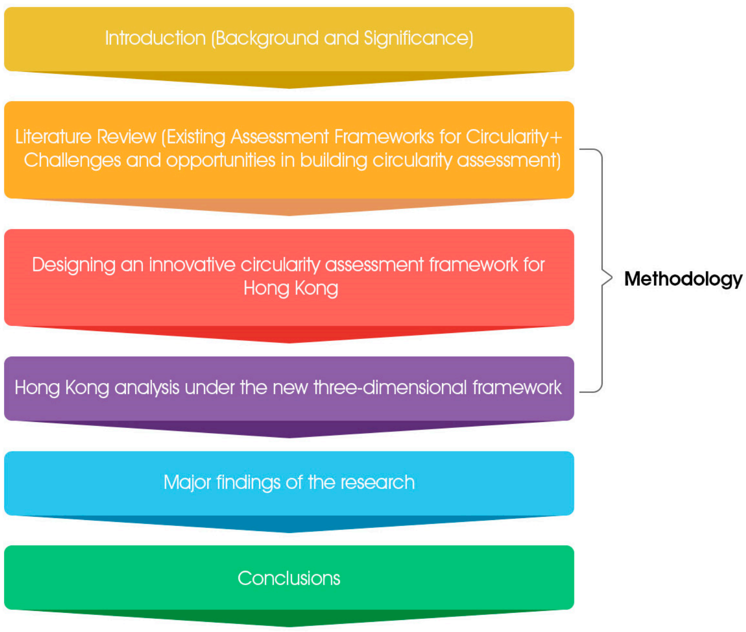

Figure 1. Research workflow of the study.

2. Literature Review

Hong Kong has spent effort on CE development in recent years, especially in renewable energy and waste management. This is mainly caused by its service-based economic structure, high dependence on mainland imported goods, and exported waste disposal [12]. Most of Hong Kong's circular policies focus on waste management, and financial incentives are designed for big corporations, bringing challenges to small enterprises [13]. However, even mature recyclers battling difficult eligibility requirements may find it difficult to access the Recycling Fund, the Environmental and Conservation Fund, and the Innovation and Technology Fund [14].

Drawing upon a diverse array of academic research, industry reports, and policy analyses, this literature review endeavours to distil key themes, trends, and perspectives that illuminate the landscape of circular building practices. To support the development of a circularity assessment index for Hong Kong, this research draws on existing frameworks, theories, and models from construction and real estate fields. These theories provide conceptual frameworks and analytical tools for understanding the flows of materials [15], energy, and resources within urban systems and assessing their environmental and socio-economic impacts. By integrating insights from these theories and models, stakeholders can develop a comprehensive and context-specific approach to assessing circularity in the built environment of Hong Kong. Circular buildings are designed for disassembling and adaptability, using sustainable materials that ensure and enable re-life options [16]. The whole circular building lifecycle includes design, build, operate, and end-of-life options, which indicates a shift from an object-centric to a system-based framework [7,17]. This means integrating circular economy principles into every aspect of the building's design, operation, maintenance, and end-of-life treatments [18]. We first examined existing frameworks for assessing circularity before developing a new one.

Existing Assessment Frameworks for Circularity

Circularity assessment is an important aspect of transitioning towards a circular economy in the building construction industry in Hong Kong. Whether qualitative or quantitative, circularity indicators can be used to assess the circularity potential of buildings and construction systems across social, cultural, environmental, and economic dimensions [19]. There are four equally weighted circularity criteria, namely, (1) carbon footprint of building materials, (2) reused content of building materials [20], (3) disassembly potential and longevity of building components use, and (4) building design flexibility and functional adaptation potential [21]. Abadi and Sammuneh proposed a new framework for circularity assessment in the architecture, engineering, and construction industries, including a material flow model and a material passport [22]. The Madaster platform and the Ellen MacArthur Foundation's Material Circularity Indicator (MCI) are also cited as tools for assessing circularity. ISO 59020 [23] also provided a new assessment standard for circularity in 2024. This research adopts a new categorisation, dividing all assessment methods into three categories (Table 2): material-based, technology-oriented, and design-supported. Each method addresses different aspects of circularity, from material selection and lifecycle management to technology and design principles.

2.1. Material-Based Circularity Assessment Methods

The material flow method focuses on tracking and optimising the use of materials within the construction industry to minimise waste and maximise reuse and recycling. These methods assess the flow of materials through various stages of the building lifecycle, from extraction and processing to construction, usage, and eventual disposal or recycling. It helps understand material inputs and outputs, thereby identifying inefficiencies and opportunities for improving material efficiency and sustainability.

Table 2. Summary of the literature review.

Literature Review of Building Circularity Assessment Frameworks		
Material-Based	**Technology-Oriented**	**Design-Supported**
Denmark Circularity Indicator Framework	Platform CB'23	Design for Circularity Framework
Material Circularity Indicator (MCI)	Madaster Circularity Index	Circular Building Assessment Prototype (CBA)
New Material Flow Model	Circular Economy Meter (CE Meter)	Design Criteria for Circular Buildings
Environmental Performance Assessment Method for Construction Works	Circularity Calculator	Circular Construction Evaluation Framework (CCEF)
Material Reutilisation Score (MRS)	Disassembly and Deconstruction Analytics System (D-DAS)	Building Research Establishment Environmental Assessment Method (BREEAM)
Longevity and Resource Duration		Leadership in Energy and Environmental Design (LEED)
Building Circularity Indicator (BCI)		Level(s) Framework
Circular Economy Indicator Prototype (CEIP)		Reversible Building Design Protocols
Cradle to Cradle® (C2C) Certified™ Framework		Circular Design Guide
Circular Life Cycle Sustainability Assessment (C-LCSA) Framework		ISO 59020

The lifecycle approach in the context of Hong Kong's built environment refers to evaluating and managing the environmental impacts of a building throughout its entire life—from design and construction through operation to demolition [24]. This approach emphasises reducing embodied carbon and construction and demolition (C&D) waste, which is crucial given that 71% of Hong Kong's carbon emissions come from the built environment [25]. The lifecycle assessment (LCA) helps identify opportunities for improving energy efficiency, reducing material use, and enhancing the overall sustainability of buildings. Vermeulen et al. (2019) [26] expanded the R strategies to 10R with a detailed description, while Zhang (2021) [22] summarised 11R by adding Rethink. R-strategies are important for design adaptability and deconstruction at the end life of buildings [15].

2.1.1. Denmark Circularity Indicator Framework

The Denmark Circularity Indicator Framework offers a sophisticated tool for assessing circularity, particularly within the scope of circular buildings. This framework provides a standardised methodology to evaluate how effectively resources are utilised, minimise waste, and create value throughout a building's lifecycle. Key indicators such as Net Additions to Stock, Non-Renewable Biomass Inputs, Non-Circular Input, Ecological Cycling Potential, Non-Renewable Inputs, Recyclable Materials, and Socioeconomic Cycling [1] allow for a detailed analysis of building materials and processes. This enables stakeholders—including architects, developers, and policymakers—to track circularity progress and identify key areas for improvement in building design and construction.

A significant advantage of the Denmark Circularity Indicator Framework in the realm of circular buildings is its holistic and multi-dimensional approach. This comprehensive perspective allows stakeholders to consider end-of-life strategies for building materials, such as reuse and recycling, while also optimising resource efficiency during the construction and operational phases. The framework's data-driven approach offers precise insights into the circular performance of buildings, enabling informed decision making for sustainable design, construction, and retrofitting projects.

Despite its strengths, its complex structure and data-intensive approach can be particularly challenging for small and medium-sized enterprises (SMEs) in the construction sector, which may lack the resources or expertise to conduct in-depth analyses. The framework's reliance on specialised data can create barriers for smaller firms adopting circular building practices, making it less accessible without significant external support.

2.1.2. Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI) of the Ellen MacArthur Foundation (EMF) is a metric used to assess the circularity of materials within the built environment. It is based on two cycles: the technical cycle, which focuses on the recycled properties of materials, and the biological cycle, which considers environmental impacts. Four categories of MCI scores are available: Circularity, Value Capture, Recycled Content, and Reuse Index [27].

The MCI evaluates several key material use and management aspects, including recyclability, reusability, renewability, durability, and resource efficiency. It considers whether materials can be easily recycled at the end of their life cycle. Materials that can be efficiently recycled and reintroduced into the production process are considered more circular [2]. It looks at whether materials can be reused in their current form or repurposed for other applications without significant processing. Reusable materials contribute to circularity by extending their lifespan and reducing the need for new resources.

These metrics provide clear, quantitative metrics that can assess and compare the circularity of different materials and products. They help track the performance of circular economy strategies over time, identifying areas for improvement. However, the method may not capture all aspects of sustainability, such as social impacts or broader environmental effects beyond material use. Moreover, the variability in how MCIs are calculated and applied can lead to inconsistencies and difficulties in comparing results across different projects or organisations.

2.1.3. New Material Flow Model

The building circularity material passport (BC MP) is a new material flow assessment method integrating a material flow model, a material passport (MP), and a building circularity (BC) calculation method to evaluate and enhance the circularity of building projects [22]. The BC MP outlines necessary data for assessment, while the BC calculation method offers equations for scoring circularity. Material passports integrate with Building Information Modelling (BIM) and identify reusable and recyclable construction materials and products in pre-demolition audits [28].

The BC MP method provides a holistic view of a building's material flows, enabling thorough analysis and identification of circularity opportunities throughout the building's lifecycle. The material passport ensures that all relevant data about building materials are readily accessible, promoting transparency and facilitating more informed decisions regarding material reuse and recycling [29]. The method aligns with broader sustainability targets, such as reducing waste and carbon emissions, thereby contributing to environmental goals at both local and global levels [30].

The comprehensive nature of the BC MP method can lead to complex implementation processes, requiring significant time and resources to collect and manage detailed material data [22]. Establishing the necessary infrastructure for tracking material flows and maintaining material passports can involve substantial initial investments, which might be a barrier for smaller projects or firms. The effectiveness of the BC MP method relies heavily on accurate and up-to-date data. Ensuring the integrity and consistency of these data can be challenging, especially for larger projects with numerous stakeholders.

2.1.4. Environmental Performance Assessment Method for Construction Works

The Environmental Performance Assessment Method for Construction Works in the Netherlands is a standardised approach to evaluating the environmental impacts of construction projects [31,32]. This method, managed by the Dutch National Environmental Database (NMD), provides a uniform, unambiguous, verifiable, and reproducible means to calculate and compare the environmental performance of various structures [32,33]. There is no requirement for the construction method and technology in the assessment method because it is performance-oriented, not solution-oriented.

The method enables consistent environmental performance assessments across different projects, ensuring comparability and transparency [32]. This creates a level playing field for all stakeholders involved in construction [32]. It incorporates the European standard EN 15804, which includes methodical requirements for Environmental Product Declarations (EPD). This ensures a comprehensive assessment of a product's environmental impact throughout its life cycle. Specific guidelines for renovations and transformations are provided, ensuring these projects are evaluated rigorously as new constructions [32].

The comprehensive nature of the assessment, which includes detailed LCA and EPD requirements, can be complex and time-consuming, particularly for smaller projects or firms with limited resources [34]. The method relies heavily on accurate and detailed environmental data, which can be challenging to obtain and verify, especially for non-standard materials or innovative construction techniques [32]. Implementing the assessment method can involve significant initial costs for data collection, software, and training, which might be a barrier for some stakeholders [35].

2.1.5. Material Reutilisation Score (MRS)

The Material Reutilisation Score (MRS) offers a nuanced understanding of the potential for materials to be reused, recycled, or composted at the end of their lifecycle [36]. This score evaluates the degree to which materials can be returned to the material stream without losing quality or value, thereby ensuring their continued use. Commonly assessed materials within the MRS framework include glass, paper, aluminium, steel, and other recyclable construction components. The MRS calculation is based on two primary variables: intrinsic recyclability (IR), which measures the inherent capability of a material to be recycled, and recycled content (RC), which reflects the proportion of a material sourced from recycled inputs.

The MRS framework is particularly valuable for professionals in the built environment, such as architects, designers, and builders, as it provides a quantitative metric to guide material selection based on their end-of-life potential. This facilitates informed decision making during the design and construction phases, contributing to the creation of buildings that are resource-efficient and capable of meeting green building certifications like LEED and BREEAM [37]. The MRS framework not only supports regulatory compliance but also aids in achieving broader sustainability goals.

However, the effectiveness of MRS depends heavily on detailed information about the materials used, including their composition, properties, and potential end-of-life scenarios—data that can be difficult to obtain, especially in complex construction projects. Additionally, while the MRS effectively addresses the end-of-life potential of materials, it may overlook other environmental impacts associated with the production and operational phases, such as embodied carbon and energy consumption.

2.1.6. Longevity and Resource Duration

Resource duration focuses on the time that materials and resources remain in use within the building lifecycle. The longevity indicator measures a resource's contribution to material retention. It assesses how effectively materials are utilised and how long they serve their intended purpose before needing replacement or recycling. This method evaluates the material efficiency and lifecycle impacts [38]. Three generic components comprise the measure: initial lifetime, earned refurbished lifetime, and earned recycled lifetime. Longevity and resource duration are key concepts in assessing the circularity of the built environment.

This approach shows value-added, non-monetary performance indicators within the circular economy context. Most of the circularity assessment methods use burden-based indicators. Longevity measures the duration of material in a product system, where greater retention corresponds to greater resource efficiency. Time as a valuable resource could be measured, such as class attendance. The longevity indicator presents a simple tool to determine the value chain of a product, though it does not address the complexities in the recycling process and refurbishment [38].

Generally, the higher the material retention, the slower the loop and, consequently, the greater the contribution to the circular economy [39]. Longer-lasting buildings reduce the need for frequent replacements, conserving resources and minimising waste. Buildings designed for longevity can be adapted for different uses over time, further extending their useful life. However, designing and constructing for longevity can involve higher upfront costs. While overall maintenance may be reduced, the need for specialised maintenance practices and materials can be higher.

2.1.7. Building Circularity Indicator (BCI)

The Building Circularity Indicator (BCI) frameworks are tools used to measure and evaluate the circularity of buildings and construction projects [40]. These frameworks assess various aspects of a building's design, materials, and lifecycle processes to determine how effectively resources are utilised and how easily materials can be reused, recycled, or repurposed. BCI frameworks aim to provide a comprehensive understanding of a building's performance within the context of a circular economy. As well as examining the amount of virgin materials, the amount of unrecoverable waste, and the product lifetime, two indicators—the Building Circularity Indicator (BCI) and the Predictive BCI (PBCI)—combine the Material Circularity Indicator with Embodied Energy (EE) and Embodied CO_2 (EC) analyses Design for Disassembly (DfD) criteria [41].

This holistic assessment provides a comprehensive view of a building's circularity by considering multiple factors such as material use, design, and lifecycle impact. It encourages integrated thinking and holistic approaches to sustainable building practices. Besides promoting innovation in building design to improve resource efficiency and material recovery, it offers clear metrics and indicators supporting informed decision making for architects, builders, and policymakers.

However, it is very data-intensive, requiring extensive data collection and analysis, which can be resource-intensive and time-consuming. Accurate data on material properties, lifecycle impacts, and end-of-life scenarios are necessary for reliable assessments. Moreover, the frameworks can be complex to understand and apply, requiring specialised knowledge and expertise as they involve multiple variables and indicators that must be accurately measured and interpreted.

2.1.8. Circular Economy Indicator Prototype (CEIP)

The Circular Economy Indicator Prototype (CEIP) is a material-based assessment framework designed to evaluate circularity by focusing on aspects such as resource efficiency, waste generation, and lifecycle management [42]. While it was not specifically developed for the building sector, CEIP's metrics can be adapted to assess the circularity of buildings. It measures the proportion of recycled materials used in construction, emphasizes efficient material use, and aims to minimise waste throughout a building's lifecycle.

Additionally, CEIP evaluates practices that reduce construction and demolition waste and assesses the environmental impacts of materials from extraction to end-of-life.

CEIP offers significant advantages for circularity grading within the built environment due to its comprehensive material assessment and detailed lifecycle metrics. By promoting resource efficiency through waste reduction and emphasising R-strategies (such as reuse, repair, and recycling), it helps stakeholders to optimise material use and reduce environmental impacts [43]. This focus aligns with circular economy principles by encouraging the reuse of existing resources and minimising new resource extraction. Furthermore, CEIP's emphasis on lifecycle analysis ensures that the long-term impacts of materials are considered.

However, it may overlook critical aspects such as design principles, technology integration, and the overall performance of buildings, which are essential for a truly holistic approach to circular construction. For example, it does not inherently account for design flexibility or adaptive reuse, which are key to extending the lifecycle of buildings and reducing the need for demolition. Moreover, adapting CEIP for the built environment may require significant modifications, as it is not originally tailored to this context.

2.1.9. Cradle to Cradle® (C2C) Certified™ Framework

The Cradle to Cradle® (C2C) Certified™ framework is a material-centric circularity assessment method designed to ensure the health, safety, and reutilisation of materials within products and systems [44]. Emphasising the quality and lifecycle of materials, it aligns with the principles of circular economy by encouraging the design of products and systems that can be fully reclaimed or reused. The framework promotes a vision where waste is eliminated, and materials are perpetually cycled through reuse. This focus on continuous material cycling makes it especially relevant to the construction sector, where materials like metals, concrete, and composites can be evaluated for their recycling potential.

The C2C framework offers guidelines for evaluating material health, recyclability, and renewable content. It ensures that materials are non-toxic and pose no harm to human and environmental health. Furthermore, the framework encourages designing for disassembly, allowing materials to be easily separated and reused at the end of a building's lifecycle. By promoting the use of renewable energy in production processes, responsible water management, and respect for human rights, C2C extends beyond material concerns to include environmental and social responsibility.

However, achieving C2C certification presents challenges, particularly for smaller companies that may struggle with the resource demands of the certification process. The data collection and analysis required to meet C2C standards can be costly and time-consuming, potentially limiting the accessibility of the certification for resource-constrained businesses. Additionally, while C2C provides a thorough evaluation of material properties, it may overlook technological innovations and design strategies that are equally crucial for achieving circularity in buildings.

2.1.10. Circular Life Cycle Sustainability Assessment (C-LCSA) Framework

The C-LCSA framework integrates the principles of life cycle assessment (LCA) with circular economy concepts to evaluate the sustainability of buildings throughout their entire lifecycle. This framework aims to optimise the use of materials, energy, and resources in a way that reduces environmental impact, improves economic efficiency, and enhances social well-being, all within the context of a circular economy [45]. The developed C-LCSA framework added circularity assessment (CA) as an additional dimension to LCSA (C-LCSA = LCA + LCC + S-LCA + CA). C-LCSA is a useful tool for LCA practitioners in identifying trade-offs between improved circularity and resulting impacts on socio-economic, environmental, and economic pillars.

This framework provides a comprehensive view of a building's sustainability by integrating environmental, economic, and social dimensions. This enables stakeholders to make informed decisions based on a thorough understanding of the lifecycle impacts of building materials and practices. It promotes circularity by encouraging efficient use of resources and minimises waste through recycling and reuse. This helps reduce the overall environmental footprint of buildings by encouraging sustainable material use and waste management practices.

However, it requires extensive data on material properties, lifecycle impacts, and sustainability metrics, which can be challenging to obtain. The complex analysis and modelling require specialised knowledge and expertise. Implementation can be resource-intensive in terms of time, cost, and expertise needed for comprehensive assessments. It may be challenging to integrate with existing building practices and regulatory frameworks. To make the assessment more complex, the field of sustainability assessment is continuously evolving, requiring ongoing adjustments to the framework.

2.2. Technology-Oriented Circularity Assessment Methods

A material passport is a digital or physical document that records detailed information about the materials used in a building [29]. This includes data on materials' type, quantity, and origin and their potential for reuse and recycling. The goal is to facilitate the reuse of materials at the end of a building's lifecycle, promoting circularity in the construction industry. Material passports help stakeholders, including developers and contractors, make informed decisions about material selection and end-of-life options, thus reducing waste and supporting a circular economy. The existence of an MP at the end-of-life stage of a building can be seen as an outstanding advantage regarding recycling and reuse, thus supporting circularity and sustainability in the construction sector [46].

2.2.1. Platform CB'23

Platform CB'23 is a framework developed in the Netherlands to promote circular construction practices within the construction sector. It focuses on creating guidelines and tools for measuring circularity, designing circular buildings, and standardising material reuse through 'passports' for construction materials [47,48]. CB'23 claims the inclusion of the biological cycle. This model first classifies the materials and then calculates the circularity of each material with several different indicators. It has also developed a 'Guide for Measuring Circularity' that provides a core method for measuring circularity in the construction sector. It guides individuals or organisations involved in the construction sector to measure and assess circularity within their projects or operations. The guide provides a fundamental or foundational approach to quantifying circularity. It likely outlines key principles, methodologies, and metrics for assessing circularity within construction activities. It contains step-by-step instructions, methodologies, and examples for assessing circularity within construction projects. It may include sections on defining circularity, selecting appropriate metrics, collecting data, analysing results, and implementing improvements.

One of the advantages of Platform CB'23 is standardisation. It provides a consistent method for measuring circularity across the construction industry, making comparing and standardising practices easier [47]. These help in tracking and reusing materials efficiently, reducing waste and encouraging sustainable resource management [48,49]. The framework covers various aspects of circular construction, including design, tendering, and procurement, facilitating a comprehensive transition to circular practices. Another advantage is sector-wide adoption. By involving various stakeholders from the construction sector, it ensures broad-based acceptance and the implementation of circular principles [48].

However, complexity is one of the disadvantages for CB'23. The guidelines are often technical and may be challenging for non-experts to understand and apply effectively without additional support. The numerical results of circularity measurements can be difficult to interpret, necessitating additional benchmarks or visual aids for better comprehension [49]. Implementing these guidelines may require significant upfront investment in training and tools, as well as changes in existing processes [47]. Moreover, the construction industry's decentralised nature might hinder uniform application and lead to inconsistent implementation across different projects [49].

2.2.2. Madaster Circularity Index

The Madaster Circularity Index is a tool designed to measure the circularity of buildings and construction materials. Madaster, is a platform for the registration, documentation, and management of materials and products in the built environment [50]. The foundation of the Madaster Circularity Index is the material passport, which contains detailed information about the materials used in a building, including their composition, origin, and location within the building. The index provides a score between 0 and 100%, where 0% represents a fully linear building that ends in a landfill and 100% represents a fully circular building made entirely from recycled materials and capable of being completely reused or recycled in the future [51].

The MCI promotes transparency in the real estate market by providing clear metrics on the circularity of buildings. It covers the construction, use, end-of-life, and disassembly phases. This can enhance market credibility and support policy decisions. Highlighting the circularity score encourages developers and builders to use more recycled and sustainable materials, aligning with environmental goals. The MCI helps in 'future-proofing' buildings, ensuring that both the builder and the client benefit from a longer lifespan and reduced environmental impact.

However, the accuracy of the MCI heavily relies on the completeness and quality of the data entered into the Madaster platform. Incomplete data can lead to inaccurate scores. Estimating the future recyclability and reusability of materials can be challenging, introducing uncertainties into the circularity assessment. Implementing the MCI requires significant data collection and management efforts, which can be resource-intensive for organisations.

2.2.3. Circular Economy Meter (CE Meter)

The CE Meter is a tool or framework designed to assess and measure the circularity of buildings and built environments. For Geraedts and Prins (2015) [52], the beneficial relationship between adaptability and circularity has become increasingly urgent with global pressures on CO_2 concentration in the atmosphere. It comprehensively evaluates how well a project aligns with circular economy principles, focusing on resource efficiency, waste reduction, material reuse, and lifecycle impact. It uses digital tools to assess the circularity of construction projects, focusing on process improvements and technological integration to enhance circular practices. It also evaluates the building's capacity to adapt to different uses over time.

The CE Meter provides a thorough evaluation of a building's circularity, considering multiple aspects, from material use to operational efficiency. By promoting the efficient use of resources and reducing the depletion of natural resources, it encourages practices that minimise waste. It also realises the potential for long-term cost savings through reduced material use, lower waste disposal costs, and energy efficiency. In fact, the adoption of circular practices can enhance a building's marketability and attractiveness.

Sustainable materials and design innovations may involve higher initial costs. There are also some costs associated with implementing and maintaining the CE Meter assessment system. It requires technical expertise to accurately assess and measure circularity. More time and effort are required in the planning and design stages to incorporate circular principles. Moreover, some regions have limited availability of suitable recycled and sustainable materials. Ensuring that materials and components meet circular design criteria can be challenging.

2.2.4. Circularity Calculator

A Circularity Calculator is a technological tool designed to assess the circularity of buildings and construction projects. It evaluates how materials and resources are utilised throughout the lifecycle of a building, from the design phase to demolition and reuse. It was created by IDEAL & CO Explore and endorsed by the Ellen MacArthur Foundation [53]. Four KPIs have been developed for assessment: a Circularity indicator, a Value Capture indicator, a Recycled Content indicator, and a Reuse Index [54]. Using a product's bill of materials, the calculator calculates the impact of various circularity scenarios and determines the best business model and design options based on experimental trade-offs between circularity and value capture [15].

It provides accurate, data-driven insights into the circularity of buildings, enabling better decision making. Promoting the use of sustainable materials and practices reduces the environmental impact of construction projects. It also identifies cost-saving opportunities through the efficient use of materials and reduced waste disposal costs. By providing detailed insights into material flows, lifecycle impacts, and circularity metrics, it supports sustainable construction practices and helps stakeholders make informed decisions.

However, this method can be complex and requires a significant learning curve for users unfamiliar with lifecycle assessments and circularity metrics. Moreover, the implementation and integration of circularity calculators can be costly, particularly for smaller projects or organisations. Its effectiveness depends on the quality of data, the complexity of usage, and the scope of the assessment, which should be carefully considered when implementing this tool in construction projects [54].

2.2.5. Disassembly and Deconstruction Analytics System (D-DAS)

The D-DAS is a tool or framework designed to facilitate the process of disassembling and deconstructing buildings to maximise material recovery and minimise waste [55]. This system leverages advanced analytics to plan, manage, and optimise the deconstruction process, ensuring that materials can be effectively reused or recycled. D-DAS keeps a comprehensive inventory of all materials and components in the building. It uses data to predict the most efficient and cost-effective methods for disassembly [55]. All data involve access to the building's lifecycle data, including materials used, construction methods, and maintenance history.

The first advantage of the D-DAS is the significant reduction of waste sent to landfills by promoting material recovery and reuse. This conserves natural resources by reusing existing materials instead of consuming new ones. It also recovers valuable materials that can be sold or reused, offsetting some of the costs of deconstruction. By optimising the disassembly process to reduce labour and equipment costs, it improves the efficiency and effectiveness of the deconstruction process. This identifies and mitigates potential risks associated with the disassembly process.

However, the initial costs for D-DAS implementing the system, including technology and training, can be high. It may require investment in specialised tools and software for analytics and planning. It requires technical expertise to operate the system and analyse the data. The planning and execution of deconstruction can be more complex compared to traditional demolition. Moreover, detailed planning and careful disassembly can extend project timelines compared to traditional demolition. It is more labour-intensive.

2.3. Design-Supported Circularity Assessment Methods

By embedding circularity principles from the inception through the end-of-life phases of buildings, design-supported frameworks aim to create resilient structures that adapt to changing needs, reduce environmental impacts, and promote economic savings. However, the implementation of these methods often involves challenges such as higher initial costs, the need for specialised expertise, and the complexity of integrating diverse stakeholder interests. Despite these challenges, design-supported circularity assessment methods represent a significant step towards achieving sustainable and circular built environments, aligning with global sustainability goals and regulatory requirements.

2.3.1. Design for Circularity Framework

The Design for Circularity (DfC) Framework emphasises the importance of effective information management and stakeholder integration across the entire construction value chain, which is critical for enabling continuous circular assessment in Hong Kong. Drawing on Porter's generic value chain, this approach identifies four core elements: Inception (5A), Stakeholder Integration, Circular Design and Construction Practices, and Circular Resource Management and Perceived End-of-Life (EoL) Processes. Additionally, it includes four supporting elements: Continuous Circular Assessment, Information Management, Circular Business Models, and Technology Development [15].

The framework integrates lifecycle design as a central aspect of circularity, ensuring that each phase of the building lifecycle is considered. Scholars have emphasised that circularity assessment should adopt a lifecycle perspective to identify options that deliver the highest circular value throughout the building's lifespan [19]. This approach is critical for the creation, development, and maintenance of circular value, which is largely influenced by the initial design of the building. Adopting a shift from object-centric to system-based design approaches is crucial to achieving a more holistic perspective in the transition towards a circular economy.

Nevertheless, the existing framework has limitations. It overlooks the influence of political, economic, social, legal, and environmental factors on the transition to circularity. Additionally, it does not sufficiently account for the intricate interrelationships among core and support elements, nor does it provide specific assessment metrics for each component, limiting its applicability and influence. To address these gaps, this research proposes the development of a new framework for valuation and assessment, aiming to provide a more comprehensive approach to measuring circularity within the construction sector.

2.3.2. Circular Building Assessment Prototype (CBA)

The CBA focuses on assessing how well a building adheres to circular economy principles, which include resource efficiency, waste minimisation, material reuse, and lifecycle thinking [56]. It assesses the design of buildings to ensure they meet circularity criteria, focusing on adaptability, modularity, and ease of disassembly. This leads to measures of the extent to which a building can be easily disassembled into its component parts. The reversible connections indicate the use of non-destructive joining methods that facilitate material separation. Moreover, the method not only assesses the building's energy performance and integration of energy-saving technologies but also evaluates the implementation of water-saving systems and practices. Considering waste management, it assesses both the construction and operation stages.

The first advantage of CBA is that it provides a thorough evaluation of a building's adherence to circular economy principles. It assesses multiple aspects of circularity, including material use, design, resource efficiency, and waste management. By encouraging practices that minimise waste generation and promote material reuse, it reduces the depletion of natural resources. In the long term, it enhances potential economic savings through reduced material use, lower waste disposal costs, and energy efficiency.

However, sustainable materials and design innovations may have higher initial costs. The design and planning stages require more time and expertise to implement circular principles. Moreover, implementing circular design principles requires careful planning and coordination among various stakeholders. It requires designers and builders to have specialised knowledge and skills in circular design practices. The availability of suitable recycled and sustainable materials may be limited in some regions.

2.3.3. Design Criteria for Circular Buildings

Designing circular buildings involves integrating principles and strategies that support the circular economy, emphasising resource efficiency, waste reduction, and the reuse and recycling of materials [21]. It includes several elements such as modular design, material selection, adaptability, durability, resource efficiency, waste management, and lifecycle management. Modular design uses standardised components and dimensions to facilitate easy assembly, disassembly, and replacement. Design parts are interchangeable, allowing for easy updates and repairs. These create buildings in layers that can be independently replaced or upgraded. Moreover, buildings are designed with spaces that can be easily adapted for different uses over time. The deconstruction design of buildings facilitates the recycling of materials at the end of their life cycle.

Circular design criteria reduce waste and resource consumption, lower carbon emissions, and promote the use of sustainable materials. They involve long-term cost savings through reduced material use, lower waste disposal costs, and potential for material recovery and reuse. Furthermore, buildings designed for adaptability and flexibility can better accommodate future needs and changes, extending their useful life. This enhances the resilience of buildings to changes in use, occupancy, and environmental conditions. It further helps meet or exceed regulatory requirements for sustainability and environmental performance.

Higher upfront costs may be incurred for sustainable materials, design innovations, and construction techniques. Extensive documentation and verification are needed to ensure compliance with circularity principles, adding to administrative burdens. Moreover, designing for circularity requires careful planning, expertise, and coordination among various stakeholders, increasing project complexity. The availability of suitable materials and technologies may be limited in some regions, complicating implementation.

2.3.4. Circular Construction Evaluation Framework (CCEF)

The Circular Construction Evaluation Framework is a structured approach to assessing the circularity of construction projects [57]. It aims to promote and measure the implementation of circular economy principles in the built environment, focusing on maximising the reuse of materials, minimising waste, and enhancing the lifecycle performance of buildings. The key components of the CCEF are material selection, design for disassembly, resource efficiency, waste management, and Life Cycle Assessment (LCA). Concerning the use of materials, they should have a high percentage of recycled content, a preference for materials sourced from renewable resources, and a selection of durable and long-lived materials.

Buildings are designed in modular units that can be easily assembled and disassembled [58]. There are plans to minimise waste generation during construction and processes for deconstructing buildings at the end of their life to maximise material recovery and reuse. The use of standardised building components to facilitate easy replacement and reuse allows materials to be separated without damage. Strategies to optimise the use of materials and reduce waste during construction minimise energy consumption. The CCEF encourages the use of sustainable materials and practices.

However, the framework can be complex to implement, requiring significant expertise and coordination among various stakeholders. Higher upfront costs may be associated with sourcing sustainable materials and implementing circular design principles. It also requires extensive data. The availability of circular materials and technologies may be limited in some regions, posing challenges to implementation. Variability in regulations and standards across regions can affect the application of different materials.

2.3.5. Building Research Establishment Environmental Assessment Method (BREEAM)

BREEAM is a comprehensive sustainability assessment method that evaluates various aspects of building performance, including those related to circularity. With BREEAM-C, the original green building assessment framework (BREEAM-G) was expanded into a circular building framework in 2018 [59]. It assesses buildings against several categories that directly or indirectly promote circular economy principles. Its indicators identify CE-related practices implemented and serve as benchmarks to demonstrate the integration of CE principles or strategies into the design, construction, operation, and management of buildings [60]. It encourages the use of materials with lower environmental impacts throughout their lifecycle, including those that are recycled or have a high potential for reuse.

BREEAM promotes procurement practices that consider the sustainability credentials of suppliers and materials. It also supports energy-efficient designs and systems, which indirectly relate to the efficient use of resources and waste reduction. Furthermore, BREEAM provides credits for incorporating innovative practices and technologies that support sustainability and circularity, such as modular construction and design for disassembly. The framework is adaptable to different building types and projects.

However, achieving BREEAM certification can be complex and costly, requiring significant investment in terms of both time and financial resources. Some stakeholders might find BREEAM's predefined criteria rigid, potentially limiting the flexibility to innovate beyond standard requirements. The documentation and administrative requirements for BREEAM certification can be burdensome, especially for smaller projects or organisations with limited resources. It is a broad sustainability assessment tool and may not provide as detailed guidance on circular economy principles as more specialised frameworks.

2.3.6. Leadership in Energy and Environmental Design (LEED)

LEED is a globally recognised certification system for sustainable building design, construction, and operation. It encourages the reuse of existing buildings and materials and the use of salvaged materials, reducing the need for new resources [61]. It focuses on sourcing materials with environmentally, economically, and socially preferable lifecycle impacts. Encouraging energy-efficient designs and systems that reduce operational energy use is indirectly related to the circular use of energy resources. Moreover, it promotes the use of low-emitting materials that can be recycled or reused without compromising indoor air quality. It also encourages the use of water-efficient fixtures and systems, contributing to the sustainable use of water resources.

LEED provides a broad and holistic approach to sustainability, which includes many aspects of circularity, such as material reuse, waste reduction, and resource efficiency. It enhances the market value and desirability of certified buildings. LEED encourages the adoption of innovative building practices and technologies that support circularity, such as using recycled materials and designing for disassembly. By promoting efficient resource use and waste reduction, it can lead to significant environmental and economic benefits.

While LEED includes elements of circularity, it is not exclusively focused on circularity. Other standards or frameworks may provide more detailed guidance, specifically on circular economy principles. Achieving LEED certification can be complex and costly, requiring significant investment in terms of both time and money. This can be a barrier for some projects, particularly smaller ones. Moreover, the LEED certification process can be lengthy and bureaucratic, which may discourage some project teams from pursuing it.

2.3.7. Level(s) Framework

The Level(s) framework is a European Union (EU) initiative to promote sustainability and circularity in the built environment. It describes a building's sustainability through six macro-objectives. Sixteen indicators can be used to track macro-objectives. Sustainability is described through many macro-objectives, including greenhouse gas (GHG) emissions, energy use, materials, water use, indoor quality, future resilience, and economic costs. It also aims to guide building projects towards greater sustainability by offering a holistic approach that integrates various aspects of circularity [28]. It includes a Whole Life Cycle Assessment (LCA) to measure the environmental impact of buildings from material extraction to end-of-life. By evaluating economic performance, it considers how buildings can adapt to changing conditions and withstand environmental stresses.

Level(s) provides a comprehensive framework that covers multiple aspects of sustainability and circularity, including environmental, economic, and social dimensions. It offers a standardised set of indicators and metrics, which facilitates comparability across different projects and regions. As an EU initiative, it aligns with European policies and regulations, making it particularly useful for projects within the EU. By focusing on circularity and resource efficiency, it encourages innovative design and construction practices.

However, the comprehensive nature of Level(s) can make it complex and challenging to implement. It requires extensive data collection and analysis, which can be resource-intensive and time-consuming. Effective implementation of Level(s) may require specialised training and expertise, which could be a barrier for some stakeholders. While Level(s) aligns well with EU policies, it may be less applicable or require adaptation for use in non-EU countries with different regulatory environments and standards.

2.3.8. Reversible Building Design Protocols

Reversible Building Design Protocols are guidelines and strategies that enable buildings to be easily disassembled, adapted, and reassembled for different uses over their lifecycle [62]. This approach aligns with the principles of the circular economy by promoting flexibility, resource efficiency, and waste reduction. The core idea is to design buildings that can be deconstructed without significant damage to materials, allowing for their reuse, recycling, or repurposing. One of the key components is modular design. Buildings are designed using modular components that can be easily assembled and disassembled [62].

The framework uses plug-and-play systems that simplify upgrades and maintenance by incorporating flexible mechanical, electrical, and plumbing (MEP) systems that can be easily adapted to new layouts or functions. This framework minimises demolition waste by enabling the reuse and recycling of building components. It also reduces the demand for virgin materials by facilitating the reuse of existing ones. There is potential for long-term cost savings through reduced waste disposal fees, lower material costs, and minimised need for new construction. Buildings retain value through their adaptability and potential for reuse.

The initial design and construction may be more expensive due to the need for high-quality materials and modular components. It requires investment in training for architects, engineers, and construction workers to adopt new methods and technologies. More complex design and engineering requirements need more documentation and record-keeping, which can be time-consuming and costly. Sometimes, the limited availability of suitable modular and recyclable materials in some regions necessitates close coordination among suppliers to ensure the compatibility and standardisation of components.

2.3.9. Circular Design Guide

The Circular Design Guide is a comprehensive framework developed to help designers, architects, and stakeholders incorporate circular economy principles into the built environment [63]. This guide provides practical tools, methods, and strategies to create buildings that minimise waste, optimise resource use, and facilitate the reuse and recycling of materials in the design process [64]. It aims to help designers create regenerative products and systems that minimise waste, focusing on long-term sustainability and resource efficiency. There are some key principles of the Circular Design Guide: design for longevity, design for adaptability, design for disassembly, material selection, resource efficiency, waste management, and lifecycle thinking.

The first advantage of the Circular Design Guide is waste reduction. By designing for disassembly and using recycled materials, waste is minimised. It lowers carbon footprint due to the use of sustainable materials and energy-efficient designs. It reduces material costs through the use of recycled components and lowers operational costs due to energy efficiency. Furthermore, buildings designed for adaptability and disassembly retain value through their ability to be updated and repurposed.

However, sustainable materials and modular construction techniques may have higher initial costs. More time and expertise are required in the design and planning stages to implement circular principles. This requires designers and builders to have specialised knowledge and skills in circular design practices. The availability of suitable recycled and sustainable materials may be limited in some regions. Varying regulations and standards across regions can complicate the implementation of circular design principles.

2.3.10. ISO 59020

ISO 59020 is an international standard outlining methodologies and indicators for assessing the circularity of buildings and infrastructure [23]. It emphasises optimising the use of materials and energy throughout the lifecycle of a building. It minimises waste generation through design, construction, operation, and deconstruction. It promotes the reuse and recycling of materials to extend their lifecycle. Furthermore, it considers the environmental impacts of materials and processes from extraction to end-of-life. ISO 59020 provides a holistic approach to circularity, covering various stages of the building lifecycle from design to demolition.

Being an ISO standard, it offers a globally recognised and consistent methodology, facilitating comparability across projects and geographies. Specifically tailored to promote circular economy principles, it helps organisations transition from linear to circular practices. Furthermore, it encourages the efficient use of materials and energy, leading to cost savings and reduced environmental impact. By focusing on reuse and recycling, it fosters innovation in design and material use. This framework provides practical guidelines and best practices for implementing circular economy principles in construction. It supports stakeholders in adopting sustainable practices and achieving their circularity goals.

However, the comprehensive nature of the standard may require significant effort and expertise to implement effectively. It requires detailed data collection and analysis, which can be resource-intensive. Moreover, implementing ISO 59020 can incur additional costs, particularly for smaller organisations or projects. The comprehensive nature of the standard may result in complexity and challenges in implementation. Significant effort and resources are required to adopt and integrate the guidelines and metrics into existing practices.

3. Challenges and Opportunities in Building Circularity Assessment

Research on circularity in Hong Kong indicates that outdated building codes and planning regulations stifle innovation in sustainable construction [65]. Existing waste management directives, often remnants of a linear economy, focus more on disposal rather than reuse [66]. Furthermore, cultural resistance to change and a preference for traditional construction methods remain significant barriers to accepting circular practices [67].

The shift to circular building practices requires substantial financial investments, which can be a significant barrier [68], particularly in contexts with more pronounced economic constraints. The lack of strong market demand for smart technologies that enable CE further discourages investment and innovation [69]. Limited access to financial resources hinders stakeholders from investing in the necessary technologies and processes for circularity [70]. These financial limitations make it difficult for companies to adopt new practices that require upfront costs, even when such investments may yield long-term benefits.

Fragmented supply chains for building materials make it challenging to implement circular practices effectively. As highlighted by the Fung Global Institute (2014) [71], fragmented and complex global supply chains inhibit the connectivity, information flow, and coordination required for effective circular business models. Market fragmentation and siloed decision-making processes create additional coordination challenges, which obstruct the adoption of holistic circular solutions [22].

There is a shortage of specialised skills and expertise necessary for implementing circular practices within the construction industry [66]. The shift from traditional construction methods to circular approaches requires a cultural change that many in the industry hesitate to embrace. Strong leadership and management support are essential for successfully implementing circular economy practices. A lack of leadership within organisations and government entities can significantly hinder progress toward circularity.

Reliable data are essential for assessing circularity [66]. Yet, such data are limited, along with a lack of standardised metrics, which complicates assessment efforts [70]. Furthermore, data management processes in Hong Kong are often unstructured, with challenges related to data privacy, security, and information flow hindering effective circularity assessment [69]. Additionally, the lack of advanced technological infrastructure limits progress. Challenges with interoperability between systems and stakeholder resistance to change further slow the adoption of circular practices [69].

On the other hand, opportunities to advance circularity assessment and promote circular building practices in Hong Kong are substantial. Technological innovations, including Building Information Modelling (BIM), the Internet of Things (IoT), and blockchain technology, offer significant potential for enhancing material traceability, transparency, and overall efficiency in the construction sector. These technologies are crucial enablers of circular practices, facilitating more effective resource management and circularity processes such as waste recycling and water reclamation [72].

To support green technology industries, targeted subsidies and incentives are essential, prioritising sectors such as green building, renewable energy, waste management, sustainable logistics, green fintech, and climate adaptation. This approach positions Hong Kong as a low-carbon, smart, and climate-resilient city, driving a digital transformation focused on sustainability. As Khadim et al. (2022) [73] emphasise, the advancement of digital technologies like BIM and open-access databases is key to improving the evaluation of circularity in building projects.

Moreover, the Hong Kong government should prioritise financial incentives and subsidies for small and medium-sized enterprises (SMEs) engaged in circular building practices. According to [13], such funding should be directed toward SMEs, as they often face barriers to entry that larger companies can more easily overcome. By empowering SMEs, the government can increase their participation in data collection efforts and facilitate their emergence as technology service providers for existing buildings, driving innovation and circular solutions across the sector.

In addition, policy interventions are vital in establishing an enabling environment for circularity. These include green procurement policies, incentives for circular economy practices, and the adoption of extended producer responsibility (EPR) schemes. Such measures can incentivise the adoption of sustainable design, material reuse, and waste reduction throughout a building's lifecycle, ensuring that Hong Kong remains at the forefront of circular economy practices in the construction industry.

4. Designing an Innovative Circularity Assessment Framework for Hong Kong

The circulatory assessment of buildings in Hong Kong, a dynamic urban environment characterised by rapid urbanisation, limited land availability, and high construction activity, needs a tailor-made design solution. From the literature review, a new holistic framework named the TMD Circularity Assessment Framework was created (Figure 2). It is designed to address the unique building and construction environment of Hong Kong by evaluating the circularity of buildings through three critical aspects: technology-oriented, material-based, and design-supported. Each dimension includes a set of metrics to quantify and measure the circularity of the built environment.

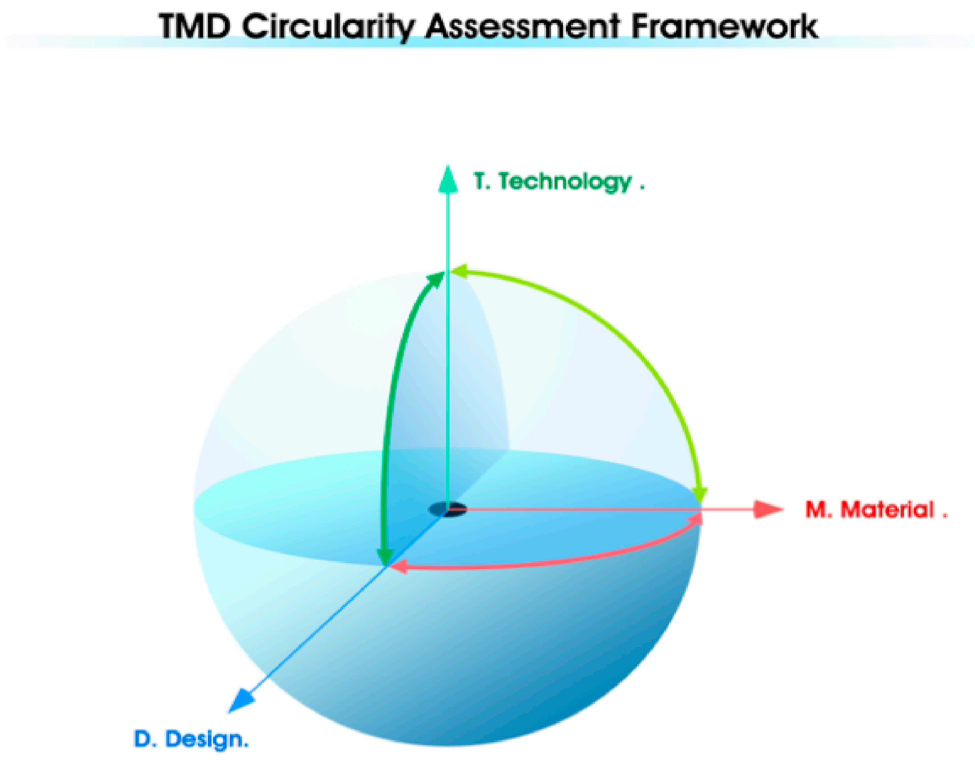

Figure 2. Perspective of the TMD Circularity Assessment Framework.

The simple formula for the calculation of the building circularity index is as follows:

$$\text{Building Circularity Index (BCI)} = \frac{T + M + D}{3}$$

where

T = Technology-oriented score (0–100);
M = Material-based score (0–100);
D = Design-supported score (0–100).

The complex formula for the calculation of the building circularity index is as follows:

$$\text{BCI} = \omega\text{T}\left(\frac{\sum_{j=1}^{m} t_j s_{tj}}{\text{m}}\right) + \omega\text{M}\left(\frac{\sum_{i=1}^{n} m_i s_{mi}}{\text{n}}\right) + \omega\text{D}\left(\frac{\sum_{k=1}^{p} d_k s_{dk}}{\text{p}}\right)$$

where

w_T, w_M, w_D = Weights for material-based, technology-oriented, and design-supported perspectives (sum of weights = 1);
t_j = Weight of the j-th technology-oriented sub-factor;
s_{tj} = Score of the j-th technology-oriented sub-factor (0–100);
m_i = Weight of the i-th material-based sub-factor;
s_{mi} = Score of the i-th material-based sub-factor (0–100);
d_k = Weight of the k-th design-supported sub-factor;
s_{dk} = Score of the k-th design-supported sub-factor (0–100);
m, n, p = Number of sub-factors in technology-oriented, material-based, and design-supported perspectives, respectively.

This formula takes into account the relative importance of each perspective and the specific factors within those perspectives, providing a more detailed assessment of building circularity.

4.1. Technology-Oriented Dimension

The technology-oriented dimension focuses on integrating and utilising advanced technologies to enhance the circularity of buildings. This dimension considers how effectively modern technologies are employed to optimise resource use, reduce waste, and improve overall sustainability. In Hong Kong, the dense urban environment and limited land resources necessitate the adoption of smart technologies to optimise space and resource management. Integrating smart building systems can significantly reduce operational costs and environmental impact by enhancing efficiency and enabling data-driven decision making. Energy efficiency technologies reduce the carbon footprint of buildings, while advanced waste management systems can help address the city's waste disposal challenges by promoting recycling and resource recovery [74].

Key Metrics:

Smart Building Systems (t1, st1): Implementation of IoT and smart technologies to monitor and manage building operations, energy consumption, and resource usage.

Energy Efficiency Technologies (t2, st2): Adoption of renewable energy systems, energy-efficient lighting, HVAC systems, and energy management software.

Waste Management Technologies (t3, st3): Use of automated waste sorting, recycling systems, and waste-to-energy technologies to minimise waste generation and improve recycling rates.

4.2. Material-Based Dimension

The material-based dimension evaluates the types and lifecycle of materials used in construction, emphasising the importance of using sustainable, recyclable, and low-impact materials. Hong Kong's construction industry can benefit greatly from adopting circular material practices due to the city's high construction and redevelopment rates. Utilising recyclable materials with low embodied energy can reduce the environmental impact of new buildings. Additionally, reusing materials from demolished buildings can help conserve resources and reduce waste, aligning with the principles of the circular economy.

Key Metrics:

Recyclability of Materials (m1, sm1): Percentage of materials used in construction that can be recycled at the end of their lifecycle.

Percentage of Reused Materials (m2, sm2): Extent to which materials are reused from previous buildings or construction projects.

Embodied Energy (m3, sm3): Total energy consumed during building materials' extraction, processing, and transportation.

4.3. Design-Supported Dimension

The design-supported dimension assesses how building design supports circularity through adaptability, modularity, and lifecycle extension features. This dimension examines how buildings can be designed for disassembly, repurposing, and longer lifespans. In Hong Kong, where space is at a premium, designing buildings that adapt to changing needs is particularly valuable. Adaptive reuse can reduce the need for new construction, preserve resources, and minimise environmental impact [75]. Modular design allows for easier maintenance and upgrading, ensuring that buildings remain functional and relevant for longer periods [71]. Incorporating features that extend the lifespan of buildings can also mitigate the environmental and financial costs associated with frequent redevelopment [76]. The definition of design is best described as "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones" [77].

Key Metrics:

Adaptive Reuse Potential (d1, sd1): Ability of a building to be repurposed for different uses over its lifespan [78,79].

Modular Design (d2, sd2): Incorporation of modular components that can be easily replaced, upgraded, or reused in other buildings.

Lifespan Extension Features (d3, sd3): Design features that extend the building's functional life, such as durable materials, flexible spaces, and ease of maintenance.

After the successful implementation of the TMD Framework (Figure 3) in the built environment in Hong Kong, the technical cycle, biological cycle, and socio-economic cycle play crucial roles in promoting sustainability, resilience, and inclusive development. The technical cycle optimises material flows and minimises waste within the built environment. The biological cycle emphasises the integration of natural processes and materials into the built environment, promoting regenerative practices that mimic ecosystems. The socio-economic cycle considers circularity initiatives' broader social and economic impacts in the built environment.

The newly developed TMD framework aims to enhance circularity in Hong Kong's built environment by incorporating key factors such as measurability, policy, regulations, modularity, adaptability, and collaboration. The R-strategies are particularly effective in improving both technical and biological circularity, and a robust circular assessment system is essential to facilitate informed decision making, as noted by Bilal et al. (2020) [80] and encapsulated by Peter Drucker's adage: "You cannot manage what you cannot measure". The literature highlights the significance of circularity assessment frameworks in driving sustainable construction and identifies the key challenges and opportunities for advancing circular building practices in Hong Kong. The TMD Circularity Assessment Framework integrates elements of the Environmental Performance Assessment Method for Construction Works and ISO 59020, ensuring consistency, comparability, and transparency in evaluating the environmental impacts of construction projects. Based on the three-dimensional perspectives, Hong Kong analyses are conducted in the following.

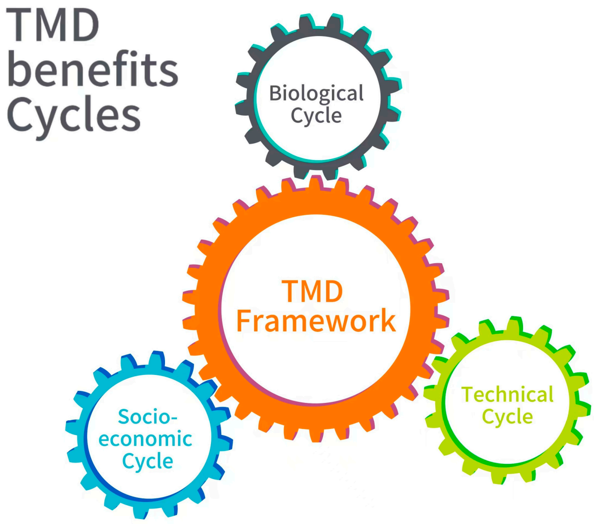

Figure 3. Enhancement of the TMD Circularity Assessment Framework in the biological cycle, technical cycle, and socio-economic cycle.

4.4. Technology-Oriented Perspective

Hong Kong is advancing its technology-oriented circularity measures through the development and application of Modular Integrated Construction (MiC) 2.0. This initiative involves collaboration with research institutions such as the Nano Advanced Materials Institute (NAMI), a subsidiary of the Hong Kong University of Science and Technology. The focus is on simplifying the connection and rebar fixing details to enhance MiC's efficiency. Since transportation and logistics planning is crucial for MiC construction, the Hong Kong Polytechnic University conducted a logistics study on MiC application in public housing developments to optimise these processes [81].

Offsite sorting facilities (OSFs) are integral to Hong Kong's strategy for improving construction waste management. Contractors can deliver their construction waste to OSFs for sorting by paying a levy, provided the waste contains more than 50% inert contents by weight. However, the Auditor's Report in 2016 highlighted the ineffectiveness of the existing inspection methodology, as sorted inert contents consistently fell below the required threshold. In response, a project aims to develop an 'AI Inspector' using big data analytics, such as fuzzy set theory and Bayesian probability models, to accurately gauge acceptable inert contents. This AI solution is expected to close loopholes in the current methodology without the need for new equipment, thereby enhancing construction waste management in Hong Kong [82].

To further improve construction waste management, a portable, handheld device is being developed to quickly and accurately estimate the composition of construction and demolition (C&D) waste. This device will enable construction managers and waste haulers to make better disposal plans without complex processes, ensuring more efficient waste management practices [83].

The AI Energy Optimisation Solution (AI-EOS) is designed to optimise energy consumption in central air-conditioning systems through big data analysis while maintaining thermal comfort for occupants. This system responds to real-time load and external weather changes, continuously monitoring and controlling different components. It also considers equipment degradation and provides support for various construction needs. The AI-EOS has been successfully applied at the Holiday Inn Express Hong Kong SoHo, achieving 30% energy savings [84].

Three-dimensional concrete printing is an emerging technology with significant potential for cost reduction, time savings, and reduced labour requirements in construction. A project by NAMI focuses on developing printable 3D concrete formulations using recycled and low-carbon materials. This includes concrete extrusion formulations designed to meet load deflection and durability requirements for applications such as outdoor furniture and wall planters. By incorporating low-carbon raw materials and recycled aggregates, this technology aims to reduce landfill burdens and support Hong Kong's transition to a greener and more sustainable environment [85].

4.5. Material-Based Perspective

The Hong Kong government has taken significant steps to adopt and promote green materials as part of its sustainability initiatives. One notable project is the 'Bio-based Carbon Negative Concrete towards Carbon Neutrality' project led by the Hong Kong government [86]. This initiative aims to achieve carbon neutrality by developing carbon-neutral or carbon-negative concrete products through the integration of Carbon Capture, Utilisation, Sequestration (CCUS), and Life Cycle Assessment (LCA) technologies. The LCA is conducted on each paving block to assess its overall embodied carbon and the effectiveness of using low-carbon raw materials [25].

The Hong Kong Housing Authority (2024) [87] has also been exploring the mass introduction of ground-granulated blast furnace slag (GGBS) as a cement replacement. This effort aims to adopt a high volume of GGBS in structural concrete components such as pile foundations and pile caps for public housing developments. Similarly, the Architectural Services Department [88] incorporates sustainable development trends and green innovations into its projects. Over the past five years, ArchSD has installed more than 175 photovoltaic (PV) systems, generating almost 1.78 million kWh of electricity annually.

In the private sector, companies like Super Bamboo Limited are exploring innovative material solutions. Super Bamboo is an extremely renewable plant that requires few resources and minimal maintenance. It can grow in poorly degraded soil, making it more resilient than other biomass materials. Additionally, upcycled bamboo scaffolding wastes can be used as raw materials for production. Being 100% bio-based, these materials will eventually biodegrade, effectively closing the life-cycle loop [89].

Research efforts in Hong Kong focused on reducing the climate impact of construction materials. One primary objective is to assess the potential of using construction and industrial waste, such as GGBS, steel slag (SS), and waste concrete powder (WCP), as alternative binders to partially replace cement in construction projects involving deep cement mixing (DCM). This research addresses the demand for measuring and reporting the embodied carbon of sustainable construction materials in Hong Kong, highlighting the importance of using locally available waste materials to minimise transportation impacts [90].

To ensure the environmental performance of materials, it is necessary to document and test materials containing recycled content for banned chemicals. Using a data template provided by a Cradle to Cradle Certified accredited assessment body, one can calculate the full environmental impact of materials. Additionally, a full social responsibility self-audit and a positive impact strategy, based on tools like the UN Global Compact Tool or B-Corp, are recommended for achieving higher levels of certification (Basic, Bronze, Silver, Gold, and Platinum).

4.6. Design-Supported Perspective

Hong Kong is making significant strides in design-supported circularity, with various initiatives and strategic frameworks aimed at promoting sustainable construction and urban development. The Architectural Services Department (ArchSD) has established a Carbon Neutrality Strategic Framework known as the '3A' Strategy. This strategy is designed to lay a solid foundation for advancing towards carbon neutrality. The '3A' Strategy consists of three core components: Amplify, Accelerate, and Act Together [91]. K11 Art Mall (K11 MUSEA) is a notable example of a building incorporating circular economy principles through innovative material reuse, green building strategies, and sustainable design elements. The building integrates sustainable design principles, biophilic elements, and nature-inspired architecture, making circularity a fundamental aspect of its overall concept [92].

Professor Edward Ng of The Chinese University of Hong Kong (CUHK) has highlighted the importance of avoiding high-density construction in the Northern Metropolis to mitigate the urban heat island effect. This region is characterised by intense heat and a lack of sea breezes. Ng recommends designing buildings with two distinct spaces: one for summer with high ceilings, large windows, and cross-ventilation, and another smaller, air-conditioned space for extremely hot weather. This design approach can help manage energy consumption while maintaining comfort [93].

The Treehouse Project, a carbon-neutral office building in a high-density, high-rise sub-tropical context, pioneers an outcome-based transdisciplinary building design framework. This framework supports the carbon neutrality of Hong Kong's building sector by 2050. It addresses complex socio-environmental sub-systems, including the urban vertical microclimate, frequent extreme climate events, and digital disruption [94].

"Enhancing liveability in a compact, high-density city" is a key focus of 'Hong Kong 2030+: Towards a Planning Vision and Strategy Transcending 2030'. One of the strategic directions is to embrace active design in the planning and design of the built environment. This approach promotes physical activity, which is crucial for preventing non-communicable diseases (NCDs) such as obesity, heart disease, and diabetes. Regular physical activity improves physical, mental, and social well-being; saves public health costs; and contributes to sustainable development by saving energy, providing cleaner air, and mitigating climate change [64].

Collaborations between industries and knowledge-sharing initiatives are essential for fostering innovation and capacity building in the circular built environment. Hong Kong's compact urban landscape offers opportunities for creating a sharing economy in the consumer goods sector. Efficient information exchange and the establishment of infrastructure for waste collection, reuse, and recovery can greatly enhance circular economy (CE) development and promote environmental efficiency [71].

Advancing Hong Kong's green taxonomy framework, outlining transition activities, and ensuring interoperability of standards are essential. Introducing KPIs related to climate neutrality and creating action plans will support these efforts. Notably, differences between architects and industrial designers have been observed, with industrial designers focusing more on circular business models and architects on the reuse of materials at the building level. Incorporating multiple perspectives from different stakeholders is vital for developing a comprehensive assessment framework [95].

5. Major Research Findings

The TMD Circularity Assessment Framework, meticulously crafted to address the distinct characteristics of Hong Kong's building and construction sector, encompasses three pivotal dimensions: technology-oriented, material-based, and design-supported

(TMD). This innovative framework aims to quantitatively measure building circularity through clearly defined metrics, thereby addressing multifaceted aspects of the built environment. By seamlessly integrating technological advancements, effective material management, and thoughtful design considerations, the TMD framework tackles economic, social, and policy challenges inherent in the construction industry, thus promoting sustainable building practices.

Government intervention is essential for nurturing circular building practices within the region [68]. Effective policies—including waste management regulations, green procurement initiatives, and circular economy incentives—serve as critical catalysts for advancing circularity goals. Nonetheless, challenges such as regulatory inconsistencies and inadequate enforcement mechanisms persist. The application of Game Theory offers a strategic approach to enhance stakeholder engagement by instituting punitive measures for waste producers and rewarding environmentally responsible practices, thereby fostering collective responsibility among stakeholders [96].

Technological innovation plays a transformative role in enhancing building circularity, with tools such as Building Information Modelling (BIM), the Internet of Things (IoT), and blockchain emerging as key enablers of material traceability, transparency, and operational efficiency [97]. Collaborative industry efforts and knowledge-sharing initiatives can facilitate the dissemination of best practices, promoting sustainability across the sector. Future intelligent circularity assessments can leverage advanced technologies, including artificial intelligence (AI) and BIM platforms, to establish automated mechanisms for evaluating and enhancing building circularity. The anticipated efficiency gains from the digital transformation of construction processes indicate that integrating circular economy tools can amplify these benefits [98].

To successfully adopt circular building practices, a delicate balance between environmental objectives and economic and social priorities must be maintained. Although the environmental advantages of circularity are evident, it is equally important to address economic constraints and social equity issues. Innovative business models, financial incentives, and robust community engagement strategies are essential for overcoming these barriers and fostering widespread adoption of circularity principles. Transitioning from a linear to a circular economy necessitates substantial investment [71]. Challenges such as the lack of expertise, appropriate metrics, and supportive policy frameworks must be navigated. Creative financial models, impact investing, and microfinance opportunities can facilitate circular economy initiatives, with institutions like the International Finance Corporation and regional development banks playing a pivotal role in bridging financing gaps.

The retrofitting of existing buildings is fundamental to transforming them into circular structures. Implementing passive building design strategies can significantly reduce energy consumption and improve thermal comfort, contributing to climate change mitigation and enhancing building resilience [76]. This process entails enforcing stringent guidelines for materials procurement, construction practices, and installations, complemented by both punitive and incentivising measures to ensure compliance. Material selection is a cornerstone of sustainable construction practices [99]. Major materials such as concrete and steel contribute substantially to upfront carbon emissions [100]. Rehabilitation efforts aim to preserve and restore existing buildings, while adaptation seeks to modify them to fulfil new functions and modern needs.

Our study aims to contribute to this global acceleration of circularity by proposing the TMD Circularity Assessment Framework, which integrates technology, material management, and design to enhance circular building practices. Some key problems for Denmark's limited success include high dependence on raw material imports, slow adaptation of circular business models, and technological limitations [1], which the TMD Framework could solve. Through designing the production–consumption pattern, innovating green materials and technologies could be a good solution for Denmark. Rather than undermining circularity efforts, Denmark's experience serves as a learning point for Hong Kong and other cities, emphasising the need for continuous improvement in circularity frameworks.

6. Conclusions

The originality of this research lies in the development of the TMD Circularity Assessment Framework, an innovative approach uniquely tailored to address the complexities of Hong Kong's building and construction landscape. This framework integrates three essential dimensions—technology, material, and design—to provide a comprehensive method for measuring and quantifying building circularity through rigorous and detailed metrics. The study illuminates the significant challenges and opportunities that accompany efforts to advance circular building practices and achieve sustainability goals in Hong Kong's construction sector. A key finding is the crucial role of forward-thinking frameworks like TMD in addressing these challenges while capitalising on emerging opportunities, thus paving the way for enhanced circularity in the built environment. The TMD Framework is pivotal in this transition, offering robust guidelines for reusing and recycling materials, which are fundamental to achieving material circularity. Technological advancements facilitate the assessment of circularity and the practical implementation of circular construction practices, playing a vital role in reshaping the sector.

This research paper contributes to facilitating circularity by inventing the TMD Circularity Assessment Framework, an innovative and comprehensive tool specifically developed for evaluating and enhancing the circularity of buildings within Hong Kong's complex environment. The framework is the first to integrate technology, design, and material, creating a circular flow that reflects the interconnected nature of these dimensions. It provides flexible metrics that are adaptable to both developed and developing countries, thereby offering valuable insights and practical guidelines for adopting a circular economy (CE) in Hong Kong's construction sector.

In terms of future research directions, new technological applications, such as BIM for automation, blockchain technology for transparency and interoperability, and AI for accuracy and efficiency in the TMD Framework, could be launched for more in-depth investigations. Moreover, the interconnectedness between each dimension and the various measurement metrics could be further identified and explored in the future.

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