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Full Length Article

Potential recyclable materials in buildings: A framework for greenhouse gas emissions assessment of residential buildings in Singapore[☆]

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ABSTRACT

As countries aim to reduce resource consumption and greenhouse gas (GHG) emissions, Whole Life Carbon Assessment (WLCA) has become a vital method for quantifying embodied and operational GHG emissions. However, few studies have conducted WLCA on an urban scale, often addressing operational or embodied GHG emissions in isolation without considering their cumulative impact. This study introduces a city-wide WLCA framework to assess the potential recyclable materials of urban building stock, using Singapore as a case study with 5915 public residential buildings. Upfront GHG emissions are calculated from material intensity and building information, while operational emissions are based on energy use and building age. Mean reference values for embodied and operational GHG emissions are set at 5901.6 tCO_2e and 22.6 kg $CO_2e/m^2.yr$, respectively. By comparing individual values and reference values, we analyse the potential recyclable materials that highlight the environmental impact of the building stock and the availability of resources.

1. Introduction

The built environment accounts for nearly half of global resource consumption and greenhouse gas (GHG) emissions, underscoring the urgent need for sustainable strategies that minimise environmental impacts (Fraser et al., 2023). As countries strive to reduce resource use, optimise building life cycles, and enhance circularity in the construction sector, Whole Life Carbon Assessment (WLCA) has become a crucial method for measuring both the embodied and operational GHG emissions of buildings and infrastructure (Izaola et al., 2023; Erin McConahey and Hbdp, 2022). WLCA involves calculating and reporting the total GHG emissions impact throughout all stages of a building's life cycle (Royal Institution of Chartered Surveyors (RICS), 2023; European Standard, 2011).

In comparison, Building Life Cycle Analysis (LCA) is a comprehensive methodology that assesses a variety of environmental impacts, including water usage and toxicity, from "cradle to grave". WLCA, on the other hand, is a specific application of LCA that focuses exclusively on quantifying GHG emissions — both embodied emissions from materials and construction and operational emissions from energy use — using standardised modules. The primary difference between WLCA and Building LCA lies in their scope: LCA covers a wide range of environmental impact categories, while WLCA specifically targets carbon dioxide equivalent (CO_2e) emissions throughout the asset's lifespan.

However, despite increasing recognition of its importance, only a limited number of studies have conducted WLCA's and building LCA's on an urban scale (Seyedabadi and Eicker, 2023; Su et al., 2022). Papageorgiou et al. (2024) introduces a highly data-dependent Urban Metabolism-Life Cycle Analysis (UM-LCA) approach to support circular strategies at the urban scale. Christoforatos et al. (2025) present a sophisticated framework for building LCA, which is highly reliant on BIM models and EPDs. Existing WLCA research in the literature, where the operational and embodied GHG emissions are combined, is reliant on high-quality data or does not operate at an urban scale (Wong et al., 2024; Khadim et al., 2023). The existing literature highlights the need to enhance efficiency, as the traditional comprehensive building-by-building approach is time-consuming and costly. Furthermore, studies should consider the continuous evolution of urban stock and incorporate dynamic WLCA indicators into urban decision-making processes.

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Cities account for significant energy use and GHG emissions, making it increasingly important to perform WLCAs on an urban scale (Mastrucci et al., 2017). Numerous studies have been conducted in this area, exploring the environmental impacts of building components as well as urban networks at the city scale (Lotteau et al., 2015). Mirabella et al. (2019) highlights the main research challenges in urban scale LCA's are to define suitable system boundaries and select an appropriate functional unit that can account for the dynamic nature of urban environments. In addition, it is crucial to ensure sufficient data granularity and to structure the life cycle inventory efficiently (Stephan et al., 2022; Fivet et al., 2024), enabling accurate identification of potential hotspots at both macro and micro levels.

The academic literature on city-wide emissions, energy use, and energy efficiency is limited compared to studies at the national level (Su et al., 2022). The choice of LCA data offers varied results in GHG emissions assessment, and the benchmarking for the same typology of buildings varies between different regions (Jungclaus et al., 2024).

This study focuses on Singapore, a high-density tropical city-state where built environment emissions and resource management are key concerns. Between 2010 and 2020, Meijer et al. (2024) tracked the amount of concrete, steel, and the corresponding embodied GHG emissions in the building stocks in Singapore. They highlight that by integrating detailed material information, their quantification can significantly enhance Singapore's digitalisation initiatives for the circular economy. Design professionals can make informed decisions about material reuse/recycling based on this data, which can be connected to digital material passports. Policies that promote material circularity and reduce dependence on material imports present an immediate opportunity to improve the utilisation of secondary resources. It is possible to gain valuable insights into the material efficiency of buildings in Singapore by tracking and compiling better data on the WLCA and material flow analysis (MFA).

The Singapore Building Carbon Calculator (SBCC) (2023) is a web-based tool designed to calculate the embodied GHG emissions in buildings throughout Singapore. The calculator focuses on upfront GHG emissions associated with materials used in construction projects. SBCC's GHG emission factors are specifically tailored to mirror the GHG emissions of projects based in Singapore. It adheres to the latest green assessment methodologies and incorporates EPDs from various programme operators. The SBCC is intended for use by sustainability consultants and Green Mark Accredited Professionals (GMAP) to assess the embodied GHG emissions of construction projects. Nonetheless, there is no inventory of individual buildings with their respective embodied GHG emissions assessments for the city-state. In addition, this tool can be utilised at the building scale, and therefore is infeasible at the urban and city scale.

This study proposes a framework for evaluating GHG emissions citywide, combining both embodied and operational GHG emissions assessments to investigate the potential recyclable materials from urban building stocks. The metric proposed in the framework to evaluate is called "potential recyclable materials in buildings" (PRMB), with three building parameters—embodied GHG emissions, operational GHG emissions, and building age determining its value. The framework leverages a building material stock model and energy use data to estimate embodied and operational GHG emissions, respectively. This article presents an important part (embodied and operational GHG emissions of the individual building) that can contribute to the WLCA and circularity study for buildings in cities.

1.1. Contribution of the article

This article presents an urban building stock GHG emissions assessment and potential recyclable materials map for residential buildings in the tropical city-state of Singapore. Residential buildings comprise the majority of Singapore's building stock. This is the primary reason for selecting this building typology, in addition to data availability and support for current policy initiatives aimed at reducing GHG emissions in this sector.

The age of a building and its GHG emissions assessment provide important indicators regarding its potential for demolition. In Singapore, the age of a building, and specifically the length of its lease, is the primary factor in decisions related to building demolition as part of urban renewal policies. However, GHG emissions assessment can be a significant factor in the building demolition decision-making process. By incorporating embodied and operational GHG emissions assessment (often referred to as the product, construction process, and use stages of WLCA) into the decision-making process, resources can be more effectively planned and managed for sustainable reuse. While embodied GHG emissions are historical and decrease over time, operational GHG emissions tend to increase with the lifespan of a building. Therefore, understanding these three parameters is crucial for future decision-making and tracking the potential availability of materials for a circular economy. To achieve a circular economy, we need to recycle materials, and demolished buildings can provide a valuable source of reusable materials. Identifying which buildings should be prioritised for demolition helps us pinpoint potential sources for recycled materials.

Recycling building materials can reduce the GHG emissions of new materials during the product stage. At the same time, it creates opportunities to strategise for circularity when planning material requirements for new developments. A residential building with a high annual operational GHG emissions intensity for space conditioning, lighting, and appliances can indicate poor building performance. Although this metric alone may not justify the material recycling or decommissioning of a building (as some new constructions can also exhibit high operational GHG emissions intensity), it may signal a potential source of recyclable materials when combined with the building's age. Age is a critical factor in building demolitions worldwide, with the lifespan of residential buildings typically ranging from 50 to 60 years, and this lifespan has been decreasing over the years (Andersen and Negendahl, 2023). By visualising the relationship between building lifespan and GHG emissions, this framework motivates the prolonged lifespan of buildings.

A high score across all three parameters (embodied GHG emissions, operational GHG emissions intensity, & building age) may indicate a material-rich, poorly performing building that is old. A building with a high score represents a potential opportunity as a source of recyclable materials if decommissioned for constructing new buildings. The potential recyclable materials in buildings (PRMB) analysis framework, along with its case study demonstration, is an innovative approach presented as a strategy towards improving sustainability and promoting circularity in the built environment in this paper.

Another key innovation of the proposed framework is its integration with an Urban Digital Twin, the *GHG App*—https://ghgapp.github.io/ (Alva et al., 2024a), which enables the visualisation and analysis of GHG emissions assessment outcomes. This platform facilitates data-driven decision-making for policymakers, urban planners, and partners in the building sector. By demonstrating a scalable and regionally adaptable approach, this study provides a foundation for integrating GHG emissions assessments into urban planning, policy development, and sustainability initiatives worldwide.

1.2. Paper organisation

The research methodology in this article is explained in four parts in Section 2. The scope of the study is described in Section 2.1. In Section 2.2, the methodology framework for building GHG emissions assessment and PRMB analysis is presented. In addition, individual methodologies are explained to estimate the embodied and operational GHG emissions of buildings. In Section 2.4, the scenario of the reuse of recycled building materials in our case study is presented. In Section 2.3, three parameters for the PRMB analysis are presented in detail. Finally, in Section 3, the results of the embodied and operational GHG emissions and the analysis of PRMB are described. Section 4 discusses the results along with the limitations of the study, and is followed by the conclusion (Section 5).

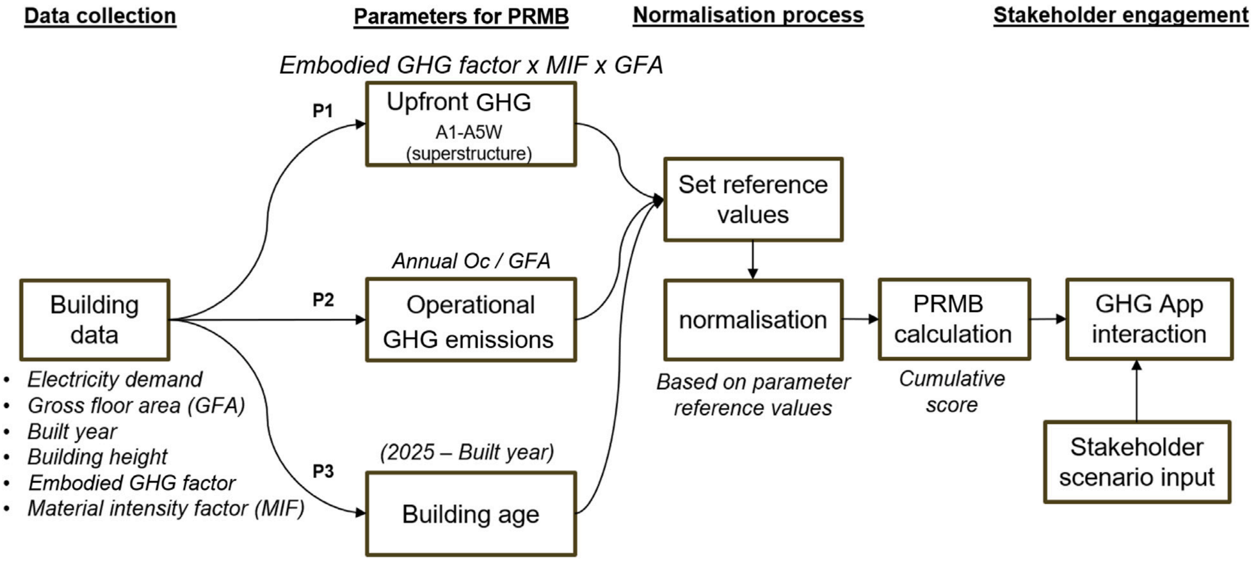

Fig. 1. Framework for potential recyclable materials in buildings (PRMB) study and stakeholder engagement. Parameter 1 (P1) refers to the embodied GHG emissions, parameter 2 (P2) to the operational GHG emissions, and parameter 3 (P3) to the building age.

2. Methodology

2.1. Scope of the study

A region-specific sample of 5915 public residential buildings of the Housing and Development Board (HDB), Singapore, was used to determine reference values for embodied and operational GHG emissions. By applying these reference values, this article develops a city-wide PRMB analysis, offering insights into resource efficiency and the long-term sustainability of the urban built environment.

The PRMB analysis shows which buildings in a city can potentially be deeply renovated or demolished, recycled as raw materials, and reused in the new construction of buildings. The PRMB can be determined using key parameters influencing building demolition, recyclable and reusable material (as shown in Section 2.3).

2.2. Framework for building GHG emissions assessment and PRMB analysis

A methodological framework is developed to study PRMB and stakeholder engagement (as shown in Fig. 1). The framework represents four stages: (i) data collection; (ii) processing of the parameters for the PRMB; (iii) normalisation and cumulative score for the calculation of the PRMB; and (iv) stakeholder engagement using the *GHG App*.

In the data collection stage, various building data such as electricity and city gas demand, embodied GHG emissions factors of building materials, gross floor area (GFA), construction year, and building height are collected. Information on the properties of public residential buildings in Singapore is collected from Housing and Development Board (HDB) (2025), and these building metadata are combined with the geometry data of the building footprint available from OpenStreetMap contributors (2017).

In the parameter stage, GHG emissions assessment is carried out in the building life cycle stages as defined in European Standard (2021) BS EN 15804:2012+A2:2019 and European Standard (2011) BS EN 15978: 2011 (as shown in Fig. A.1). The GHG emissions assessment is conducted by setting Parameter 1 (P1) – embodied GHG emissions, Parameter 2 (P2) – operational GHG emissions, and Parameter 3 (P3) – building age as parameters for the PRMB study.

Embodied GHG emissions (P1) refers to GHG emissions associated with materials and construction processes throughout the life cycle of a building or infrastructure. This includes material extraction *(module A1)*, transport to the manufacturer *(A2)*, manufacturing *(A3)*, transport to the construction site *(A4)*, construction *(A5)*, use phase (*B1*, such as concrete carbonation but excluding operational GHG emissions), maintenance *(B2)*, repair *(B3)*, replacement *(B4)*, refurbishment *(B5)*, deconstruction *(C1)*, transport to end-of-life facilities *(C2)*, processing *(C3)*, and disposal *(C4)*. Any benefits beyond the system boundary *(D)* should be reported separately to modules *A-C*.

Upfront GHG emissions (*A1-A5*) along with *B2*, *B4* and *B6* modules are referred to as the minimum scope of WLCA in the Carbon Section of the Singapore Green Mark 2021 by Building and Construction Authority (BCA) and the Singapore Green Building Council (SGBC) (2021). However, due to the lack of information available on materials, upfront GHG emissions (*A1-A5w*) are considered for *embodied GHG emissions (P1)* calculation. *A5w* refers to the emissions generated from the management of waste produced during the installation phase of a project. The mean value for the sample is derived from all upfront GHG emissions in the building.

The concrete material intensity factor (MIF) of each building is calculated based on the “parametric archetype” model (Pei and Stouffs, 2025). This model, which is based on available MIF data of several building projects from government documents and BIM models, maps the known MIF of existing buildings to other HDB building instances without such material information. The mapping rules are based on “distance measurement”, which maps MIF from the most similar buildings to those with real MIF data. The error rate of this model in predicting MIF on Singapore HDB buildings increases to 13.95%.

The MIF of steel is calculated based on the ratio of concrete to steel in public residential buildings, from existing research in Singapore. Meijer et al. (2024) specified the embodied GHG emissions factor for concrete (A1-A3=0.166, A4=0.024, A5w=0.046 in $kgCO_2e/kg$) and steel (A1-A3=1, A4=0.12, A5w=0.2 $kgCO_2e/kg$) based on the Singapore building stock. These GHG emissions factors are utilised to calculate *P1*, the embodied GHG emissions (E_c) for each building using Eq. (1).

$$E_c = GFA \cdot \sum_i f_{ec,i} \cdot MIF_i \tag{1}$$

where GFA = gross floor area of the building; $f_{ec,i}$ = embodied GHG emissions factor for specific building material i; MIF_i = Material Intensity Factor for each building material i.

Operational GHG emissions intensity (P2) refers to the intensity of emissions resulting from the use of energy *(B6)* to operate the building. Our research specifically examines module *B6* of life cycle stages as defined in European Standard (2011) BS EN 15978:2011 and British Standard Publication (2012) BS EN 15978:2012.

The operational GHG emissions (O_c) of the use stage of the building life-cycle is calculated based on the annual energy demand, emissions factors, and global warming potential of greenhouse gases using Eq. (2).

$$O_c = \sum_j D_e \cdot \varepsilon_{e,j} \cdot GWP_j \tag{2}$$

where D_e = energy demand per year (kilowatt hours per year) from energy source e (such as electricity, gas, etc.); $\varepsilon_{e,j}$ = emission factor for individual energy source e for greenhouse gas j; GWP_j = Global Warming Potential for each greenhouse gas j.

The Singapore (Energy Market Authority (EMA), 2025) publishes the annual *Singapore Energy Statistics (SES)* report with building electricity and city gas use data, along with electricity grid and gas emission factors. For Singapore, the grid emission factor is 0.412 kg CO_2/kWh, the build margin (based on the most recently built power units) is 0.394 kg CO_2/kWh, the upstream fugitive methane emission factor is 0.00207 kg CH_4/kWh, and the town gas CO_2 emission factor is 55.73 kg CO_2/GJ (≈ 0.201 kg CO_2/kWh) (National Environment Agency (NEA), Singapore, 2025). The energy data information is used and assigned to the individual buildings by merging it with the building data provided in the Property Information by the Housing and Development Board (HDB) (2025).

The annual operational GHG emissions for a building in the use stage are estimated based on Eq. (2). Operational GHG emissions intensity *(P2)* is calculated for 5915 sample buildings by dividing the annual operational GHG emissions (O_c) by the gross floor area (GFA) of the building. The reference value of 22.6 kg CO_2e/m^2.yr was set based on the mean operational GHG emissions intensity of 5915 sample buildings. Alva et al. (2024a) reported the operational GHG emissions estimation in a study previously conducted for residential buildings in Singapore.

Building Age (P3) is one of the key parameters that influence the demolition of buildings. Singapore has schemes for urban renewal, especially for ageing public residential buildings. However, concerns are growing due to resource constraints and the increasing number of ageing infrastructures.

2.3. Potential recyclable materials in buildings (PRMB) calculation

The cumulative score of potential recyclable materials in buildings ($PRMB_n$) for n number of key parameters is calculated using Eq. (3). The higher the PRMB value of a given building, the higher its potential for material availability and recycling.

$$PRMB_n = N_{P1} + N_{P2} + N_{P3} \ldots + N_{Pn} \tag{3}$$

where N_{P1} = normalised parameter 1 value, N_{P2} = normalised parameter 2 value, N_{P3} = normalised parameter 3 value, and N_{Pn} = normalised parameter n value. In this study, three parameters were selected: $P1$ (embodied GHG emissions), $P2$ (operational GHG emissions intensity) and $P3$ (building age).

The selected parameters, such as building age and emissions, have different scales, and therefore they need to be normalised prior to aggregation (Singh and Singh, 2020). Normalisation methods apply a common scale to values measured on different metrics. Max-Min normalisation (Vafaei et al., 2022) is used to aggregate these parameters; each parameter *Pn* is normalised using Eq. (4), which is a logistic function or a logistic curve that produces a characteristic S-shaped (sigmoid) curve:

$$f(Pn) = \frac{1}{1 + \exp\left(\frac{a - Pn}{b}\right)} \tag{4}$$

This curve can be adjusted using two key variables in the equation: a defines the inflection point (or midpoint) and b determines the steepness of the curve. The steepness parameter is particularly important, as it indicates the range of values over which the function significantly impacts the outcome. The selected variables a and b for each parameter *Pn* are summarised in Table 1.

Table 1
Variables used in the sigmoid function (Eq. (4)) for normalisation of three different parameters.

Parameters *Pn*	*a* (mid-point)	*b*
P1 Embodied GHG emissions	5900	900
P2 Operational GHG emissions intensity	22	5
P3 Building Age	50	3

Both variables, referred to as *a* for the inflection point and *b* for the steepness of the curve, can be modified as needed. For example, the variable *b* for the *P2* parameter is set to generate a steep curve based on its shorter range of values. On the other hand, *P1* parameter generates a shallow curve, considering that it has a long range of values. The variable *a* reflects the midpoint (0.5) of the normalised value that will be assigned to the set reference values for each parameter. For example, P1 is assigned a normalised value of 0.5 if the embodied GHG emissions in the building is 5900 tCO_2e.

The three parameters, P1 (embodied GHG emissions), P2 (operational GHG emissions intensity) and P3 (building age), are individually normalised based on their set reference values.

The mean for upfront GHG emissions (5901.6 tCO_2e) and operational (22.6 kg CO_2e/m^2.yr) GHG emissions intensity based on the sample residential buildings in Singapore is set as parameter P1 and P2 reference values, respectively. The building age P3 reference value is set for 50 years, as lifespan of residential buildings the lifespan of residential buildings typically ranges from 50 to 60 years (Andersen and Negendahl, 2023). This value also reflects the 99-year leasehold period for public housing in Singapore. Housing estates that are at least 70 years old have a voluntary early redevelopment scheme (VERS). Therefore, the maximum PRMB can only be achieved after the building's age of 70 years, i.e. closer to demolition. Accordingly, the building age parameter is normalised with buildings reaching 50 years as 0.5 and beyond 70 years as 1.0 using Eq. (4).

Finally, the calculated PRMB values are visualised in *GHG App* and used to engage decision-makers. While interacting with the *GHG App*, decision-makers can input various scenarios to see the corresponding analysis of PRMB intuitively (see Section 3.3).

2.4. Scenario of reuse of recycled building material

National Environment Agency (NEA) (2024) of Singapore reported in 2024 that 99% of the demolished building materials are recycled in Singapore. However, the recycled products from the demolition are repurposed as nonstructural building components that are not necessarily a part of the construction of the new building (as shown in Fig. 2). Despite the high rate of recycling demolished building materials, the new construction of public residential buildings is highly dependent on imported cement and steel to build their pre-cast structural elements. For this reason, it is extremely difficult to achieve circularity in the built environment sector.

To progress towards recycling of demolished building materials in new construction, Singapore is exploring substitutes for conventional building materials such as cement and sand (Housing Development Board (HDB) Annual Report 2023/ 2024 - Sustainability Report, 2024). Our study develops hypothetical material reuse scenarios to assess the PRMB for the future construction of new residential buildings. With an ideal scenario-1 of 100% of material reuse in the construction of new buildings. This is followed by scenario-2 of 75%, scenario-3 of 50% and scenario-4 of 25% of material reuse in new building construction. The PRMB is analysed using these four preset scenarios.

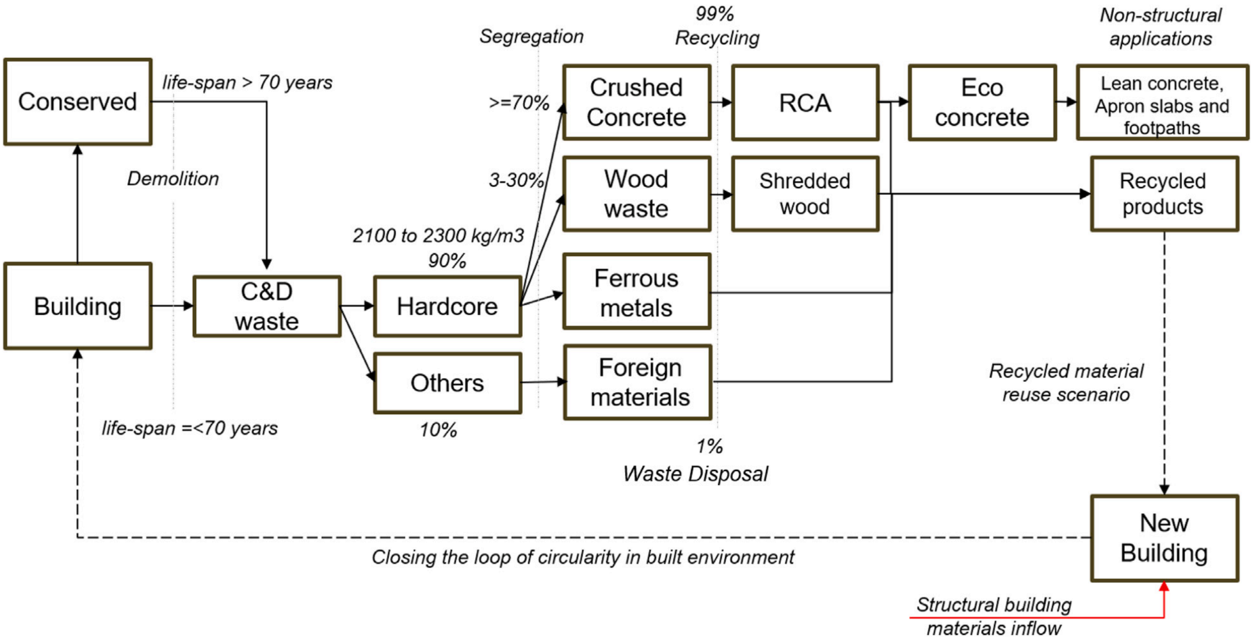

Fig. 2. Building-scale material flow analysis (MFA) for residential buildings in Singapore. Note: C&D waste=construction and demolition waste, RCA=recycled concrete aggregate. Dotted line arrows indicate an ideal scenario in which recycled materials are reused in new building construction after demolition. The red line indicates the new material inflow for the construction of a new building.

3. Results

3.1. GHG emissions assessment results

A comparison of upfront and operational GHG emissions is provided in Fig. 3. According to Singapore Green Building Council (SGBC) (2025), the distribution of GHG emissions from buildings in Singapore typically consists of 30% embodied and 70% operational GHG emissions. In the study sample with all buildings (5915 buildings), the upfront (U) to operational GHG emissions (O) ratio is 45.6% to 54.4%. With buildings 30 years and older (3904 buildings), the ratio is 39.7% (U) – 60.3% (O). With buildings 40 years and older (2382 buildings), the ratio is 36.1% (U) – 63.9% (O). For buildings 50 years and older (537 buildings), 30. 3% (U) – 69. 7% (O).

Within the sample, for buildings 30 years and younger (2181 buildings), the ratio is 56.2% (U) - 43.8% (O). Most buildings' operational GHG emissions exceed their upfront GHG emissions after 41 years. The upfront GHG emissions for all buildings fall within the 40000 tCO_2e mark, except for six buildings. Two buildings in particular have enormous embodied GHG emissions—135238 tCO_2e (built in 2009) and 94449 tCO_2 e (built in 2015), respectively, compared to other buildings, as shown in Fig. 3(a).

The mean upfront GHG emissions intensity of 373.3 kg CO_2e/m^2 and mean operational GHG emissions intensity of 22.6 kg CO_2e/m^2.yr are derived from the sample (as shown in Fig. 3(b)). The upfront GHG emissions intensity has discrete values of 265.6, 280, 280.1, 294.5, 356, 356.1, 369.5, 369.6, 384, 385, 433, and 433.1 kg CO_2e/m^2.

Previous WLCA studies of high-rise residential typologies conducted in various regions based on the respective electricity mixes used in different countries have a range of operational GHG emissions intensity between 7.9 and 45 kg CO_2e/m^2.yr (Frischknecht et al., 2020). The mean operational GHG emissions intensity of the sample buildings in Singapore presented here is in the middle of that range (22.6 kg CO_2e/m^2.yr).

3.2. PRMB results

The results show that PRMB generally increases with the age of the building (as shown in Fig. 4). This is due to the assumption that as buildings are towards the end of their use stage of life-cycle, their building materials are available for recycling and disposal. This material availability is considered an opportunity for potential recyclable materials in new construction. However, not all old buildings are meant for demolition, and in the reuse process, a few buildings have heritage value or can be repurposed.

Singapore has conserved several buildings because these buildings represent the local identity and historical relevance, and have been repurposed. The conserved buildings are a clear exception in the PRMB results and are marked separately. These buildings are not considered for the PRMB analysis as they tend to have a building life expectancy beyond 100 years. Furthermore, individual comparisons of the PRMB results with the embodied GHG emissions (Fig. 4(a)) and operational GHG emission intensity (Fig. 4(b)) are presented.

Scenarios of hypothetical material reuse are developed to assess PRMB for the future construction of new residential buildings (as shown in Fig. 5). With an ideal scenario-1, there are 966 buildings in the top quantile (top 20% of the distribution) with very high PRMB values. Scenarios 2, 3 and 4 have declining numbers of buildings with very high values: 478, 280 and 226, respectively. This suggests that fewer buildings are available for recycling in scenario 4 than in scenarios 1, 2 and 3. Scenarios 2, 3, & 4 can lead to not fulfilling the material demands of new construction in the future. New construction will then rely heavily on the inflow of materials.

3.3. GHG app dashboard

The results of the PRMB analysis are integrated on the *GHG App*, an Urban Digital Twin that enables visualisation and analysis of the outcomes of GHG emissions assessments for the building stocks in Singapore. In its early stages, the GHG App was used as a platform to estimate and visualise operational greenhouse gas emissions of the built environment and apply building renovation strategies in Singapore (Alva et al., 2024a).

The GHG App dashboard and its user experience (UX) have been designed as a web browser application utilising Cesium Ion, an open cloud platform for hosting 3D geospatial data. Cesium Ion efficiently tiles large volumes of high-resolution 3D content using the 3D Tiles

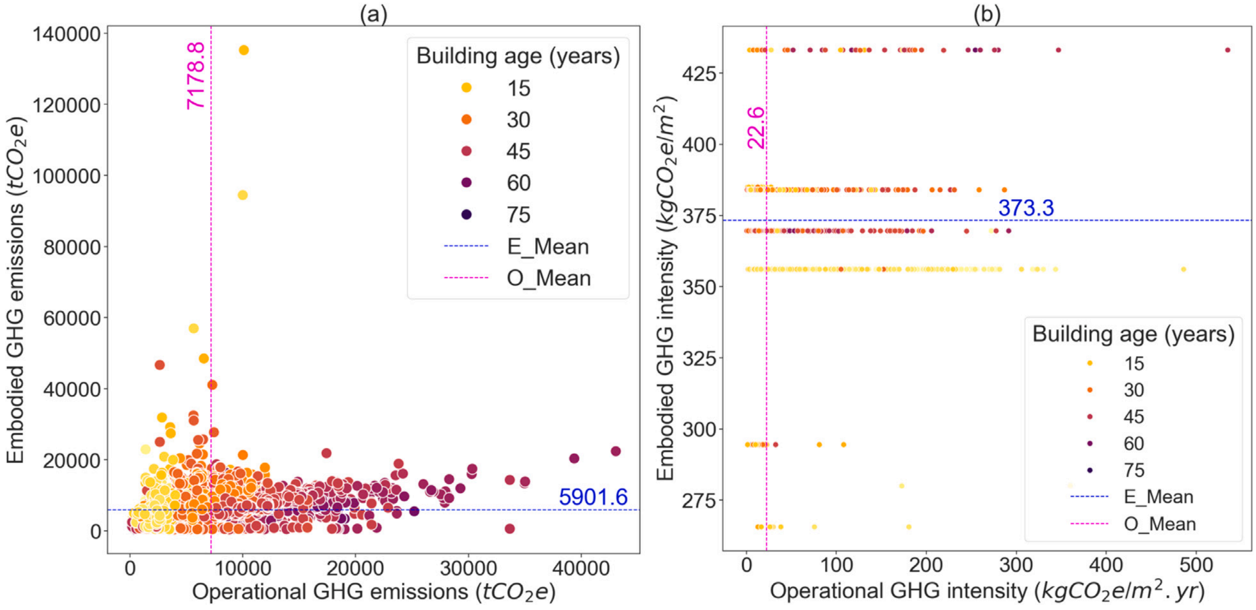

Fig. 3. A comparison of (a) accumulated operational (x-axis) and upfront embodied GHG emissions (y-axis); (b) operational (x-axis) and upfront embodied GHG emissions intensity (y-axis). The respective means for operational and upfront embodied GHG emissions are marked in pink and blue coloured dotted lines.

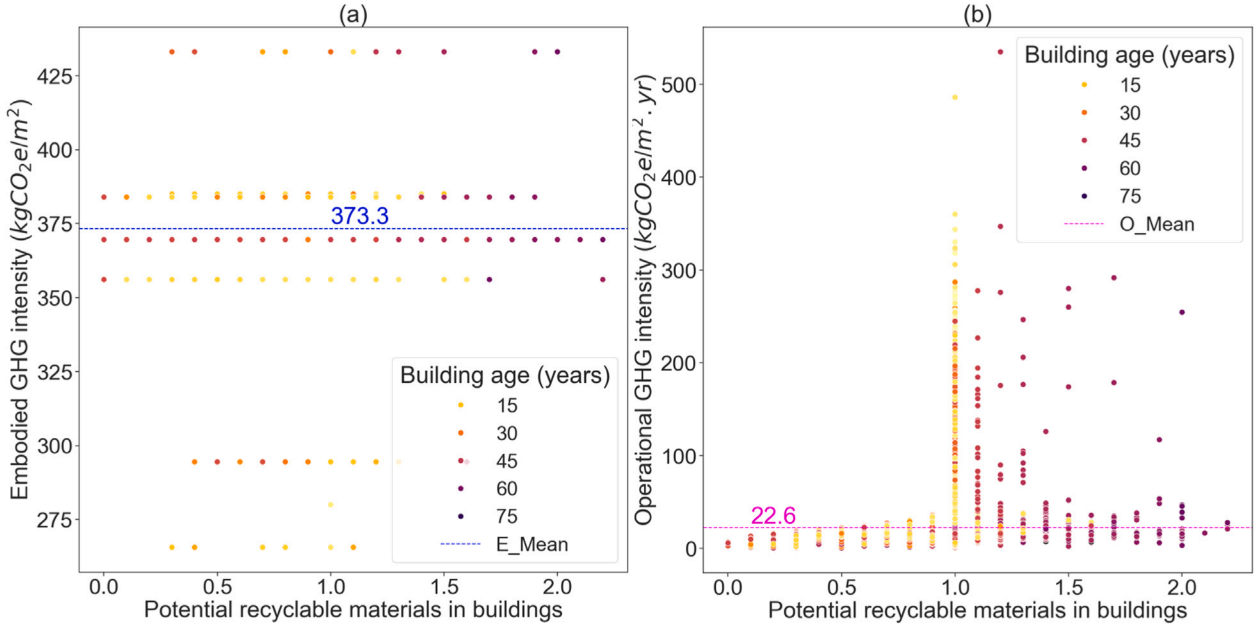

Fig. 4. A comparison of PRMB results (x-axis) with (a) upfront embodied and (b) operational GHG emission intensity (in y-axes).

format specification, which allows for optimised and rapid streaming over the web. The GHG App is customised and programmed using CesiumJS, an open-source JavaScript library. Additionally, Highcharts JS, a JavaScript charting library, is employed to create interactive visualisations on the dashboard. In the GHG App, all features are integrated with their pertinent information, utilising a 3D city dataset that has been optimised for web streaming based on a framework tested during our pilot case study (Alva et al., 2023). This framework leverages Quantum Geographic Information System (QGIS) software to combine shapefiles with building geometry and associated attributes from various data sources and formats (Alva et al., 2024b; Pei and Stouffs, 2025). Subsequently, the Feature Manipulation Engine (FME) software converts the combined shapefile into the required 3D Tiles format.

Currently, the GHG App is used to show the results of the embodied and operational GHG emissions assessments for Singapore buildings and to demonstrate the PRMB analysis executed as shown in Fig. 6. The app helps to find various patterns and clusters of high values in the analysis of PRMB. It allows users to easily navigate the different administrative areas of Singapore and visualise the GHG emissions assessments and PRMB results.

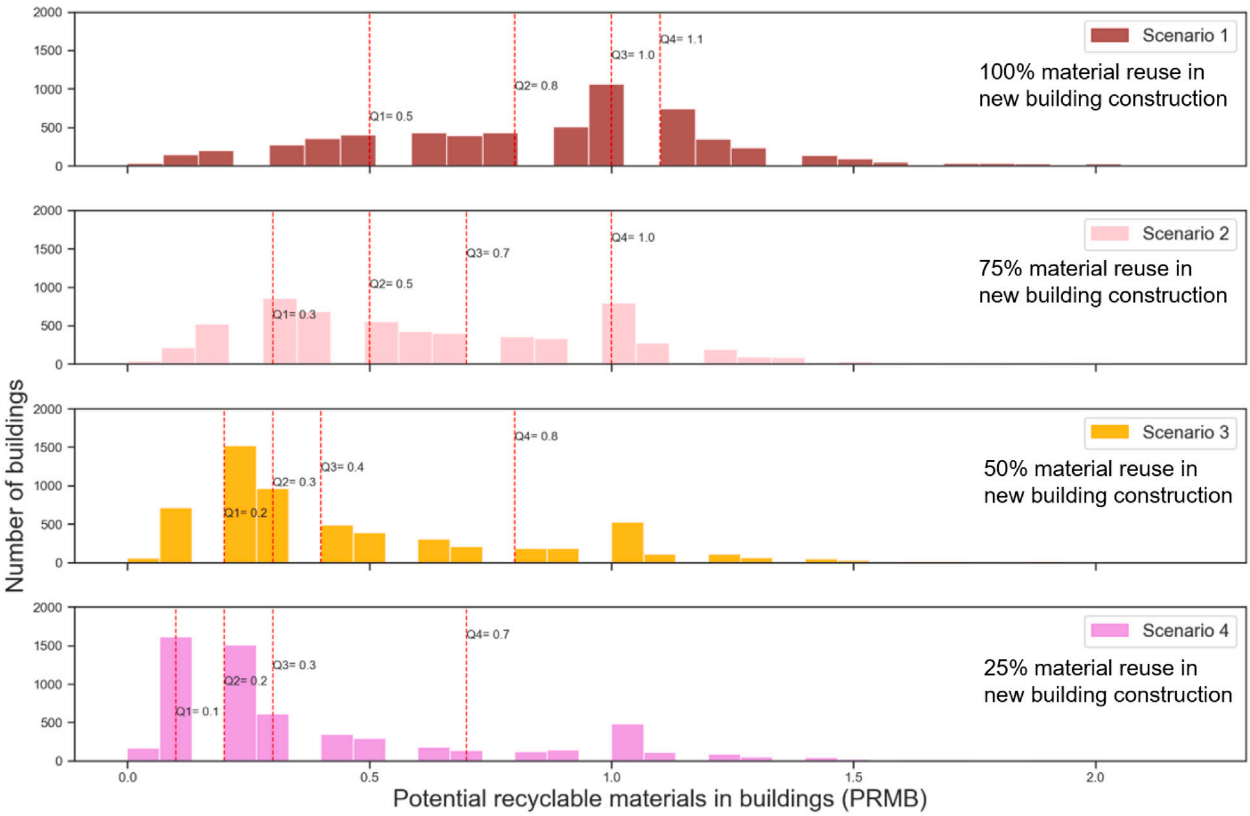

Fig. 5. Scenarios of material reuse in new building construction based on the PRMB analysis. The *x*-axis represents the PRMB results, and the *y*-axis depicts the number of buildings (frequency) corresponding to the PRMB values. Red dotted lines mark the quantiles for respective scenarios.

Fig. 6. GHG App dashboard showing the results of PRMB analysis. The decision-makers can filter the urban building stock based on the planning area of the city. The buildings highlighted in yellow have very high PRMB values.

4. Discussion

WLCA for large building stocks requires a simplified methodology that maintains interpretive rigour. The PRMB metric developed in this study incrementally enhances traditional WLCA by moving from emissions accounting to strategic urban resource management (Alva et al., 2025). It does this by integrating embodied GHG emissions (P1), operational GHG emissions intensity (P2), and building age (P3) into a composite indicator included in the — *GHG App* — digital twin platform. The PRMB conceptualises buildings as material reservoirs, operational energy consumers, and maturing stocks of anthropogenic materials. In material stock and urban metabolism research, embodied GHG emissions often serve as a weighted proxy for the total material throughput, particularly in structural systems dominated by concrete and steel, where emissions correlate with mass (Mastrucci et al., 2017; Mirabella et al., 2019; Fivet et al., 2024). Within this context, embodied GHG emissions represent the historical environmental investment embedded in structural materials and provide an estimate of material stock magnitude at the city scale.

However, it is crucial to differentiate between material stock availability and technical recyclability. Although embodied GHG emissions generally correspond to the quantity of materials, they do not account for factors such as material recycling energy (Saghafi and Hosseini Teshnizi, 2011), material contamination or degradation (Sormunen and Kärki, 2019), the complexity and hierarchy of material assemblies (Vefago and Avellaneda, 2013), design features that facilitate disassembly (Roithner et al., 2022), or market demand for secondary materials (Simpson, 2010; Nußholz et al., 2019). A building with high embodied GHG emissions may contain significant volumes of materials, but those materials may not be technically or economically feasible for high-value reuse. Therefore, PRMB should not be viewed as a trigger for demolition or a measure of circular performance. Prematurely decommissioning buildings with substantial embodied GHG emissions can lead to increased life-cycle emissions if operational inefficiencies could be addressed through deep renovation, as indicated by the embodied-operational trajectories presented in this study. The PRMB metric is best understood as a strategic screening tool that identifies material-dense, ageing, and GHG emission-intensive assets that require further assessments of structural, technical, economic, and circular feasibility. In this regard, PRMB serves to prioritise investigations rather than dictate demolition decisions.

Research on dynamic material stock analysis (B. Müller, 2006; Pauliuk et al., 2013) and city-scale LCA–GIS integration (Göswein et al., 2018; Stephan and Athanassiadis, 2017) has shown that the distribution of embodied GHG emissions closely follows the accumulation of anthropogenic materials. This relationship can provide insight into the scale of potentially recoverable resources within the built environment. Recent circular economy frameworks for buildings (Pomponi and Moncaster, 2017; Minunno et al., 2020) identify embodied GHG emissions as an important indicator of material intensity, distinguishing it from metrics related to direct recyclability or reuse. In this context, embodied GHG emissions are considered not as a technical coefficient of recyclability, but as an environmental proxy that reflects material quantity and historical production investments. The PRMB metric aligns with this literature by framing embodied GHG emissions as a weighted material stock indicator. It also explicitly acknowledges that the actual potential for recycling depends on factors such as the condition of the material, the feasibility of disassembly, and market influences that extend beyond the impacts at the production stage.

WLCA quantifies both embodied and operational emissions, providing a consistent framework for evaluating trade-offs throughout a building's life cycle. Unlike single-stage carbon metrics, WLCA allows for comparisons between renovation and demolition, highlights the timing of emissions, and identifies shifts in burden across production, operational, and end-of-life stages. WLCA is valuable for informing long-term decarbonisation pathways by distinguishing short-term emission reductions from cumulative life-cycle impacts, especially in ageing buildings. It ensures methodological transparency and comparability through standardised system boundaries, which is essential for policy alignment. Even when derived metrics such as PRMB use WLCA outputs, the underlying calculation is crucial for accurate accounting of material quantities and emissions, making WLCA the foundation for effective planning and assessment in carbon management.

Modern residential buildings tend to have higher embodied than operational GHG emissions as they meet the regionally set operational energy use standards (Shinde et al., 2024). According to the sample study, if buildings are decommissioned below 45 years, they are more likely to have higher embodied than operational GHG emissions (as shown in Fig. A.2a). This leads to material perspectives that require extending and preserving the functional lifespan of buildings to be rational with embodied GHG emissions. Singhvi et al. (2025) emphasises that as long as the construction of new neighbourhoods surpasses demolition, recycling and reuse cannot meet the material demand. Therefore, maintaining the ratio of material demand for new construction and building demolition for potential recyclable materials becomes crucial to efficient resource management.

The sustainable option is to renovate to improve the building's performance and utilise the space for a longer lifespan before decommissioning. Alternatively, after building decommissioning, materials need to find their way into new building construction through recycling or re-use. This ideal scenario can only be achieved through long-term planning towards circularity in construction processes. Prioritising the renovation of buildings can be beneficial for cities, as decommissioning a building for recycling does not fully solve the issue of underutilising the high embodied GHG emissions in place. Deep renovation or repurposing of buildings to prolong their lifetime can only justify the high embodied GHG emissions for buildings. Renovations can, in addition, rectify the issues related to high operational emissions. The GHG App demonstration can be used for stakeholder engagement and interaction with those interested in resource management and building circularity-related decision-making processes. Scenario modelling and PRMB results can help decision makers quantify the material available for recycling in case of decommissioning (as shown in Fig. 5). In addition, it can help to plan the needs of new construction based on the current building stock, with various alternative material reuse conditions. GHG App can visualise buildings with high PRMB values, emphasising the need to strategise towards the decommissioning process to fulfil recycled/reusable material needs for new construction. The PRMB analysis can help in the current building auditing work that takes place before decommissioning processes. Guidelines and strategies for reducing emissions are further communicated to the public and users of the GHG App using a conversational agent trained in the context of GHG emissions and local regulations. The conversational agent interactively presents the research output to decision-makers through customised responses based on training data such as academic publications, annual public reports from government agencies and organisations (Future Resilient Systems (FRS) programme, Singapore, 2024).

Life Cycle Inventory (LCI) methods for calculating embodied environmental flows differ mainly in data granularity and system boundaries, which can affect PRMB results. There are three primary methods: Process-based, Input-Output, and Hybrid LCI approach. (i) Process-Based LCI (P-LCI) is a "bottom-up" approach that maps individual unit processes, such as raw material extraction and manufacturing. It is highly specific and accurate when assessing direct impacts. However, P-LCI suffers from "truncation error", as it often excludes supply chain elements and overlooks upstream indirect environmental impacts (Lenzen, 2000; Crawford, 2008; Majeau-Bettez et al., 2011; Crawford et al., 2018). Studies that solely rely on process analysis often fail to account for the environmental impacts associated with inputs and outputs outside the defined system boundaries. This omission becomes crucial when comparing different material compositions, as truncation errors can vary widely across materials. (ii) Input-Output LCI (IO-LCI) method utilises national economic input–output tables to create a "top-down" view of financial flows between sectors. It is faster and captures the entire supply chain, which helps prevent truncation. However, this approach is highly aggregated, making it difficult to distinguish between specific products, such as buildings and their components. (iii) The hybrid LCI approach combines both process and IO methods to take advantage of their respective strengths. It uses detailed and specific data from P-LCI for major inputs, while filling in gaps for minor or upstream components with aggregate, top-down data from IO-LCI. The study presented in this article relies heavily on process analysis-based embodied GHG emissions calculations using MIFs, which do not fully encompass the system boundaries. Embodied environmental flows that extend beyond these boundaries can influence the results of the PRMB. To enhance understanding of these impacts, it is recommended that this study, grounded in the P-LCI approach, be replicated using hybrid data (Crawford et al., 2022, 2024) and methodologies.

Limitations of the study: This study utilises upfront GHG emissions (A1-A5w) to estimate the embodied GHG emissions, primarily due to a lack of information on materials. However, the equations and framework presented in this article apply to the full scope of embodied GHG emissions. Although the proposed framework applies to other building materials, this study focuses on Singapore's public housing buildings, which predominantly use pre-cast and cast-in-situ concrete systems constructed with concrete and steel.

The total embodied GHG emissions of a typical high-rise public housing building are not significantly impacted because concrete and steel make up over 90% of the overall structure. However, when other building typologies are examined, the importance of different materials becomes more pronounced. In Singapore, concrete and steel remain the dominant materials in the building sector. Recovering materials from buildings, aside from concrete and steel, can be challenging due to the complex assembly of mixed materials (Fernández, 2007; Göswein et al., 2018). From a recycling standpoint, concrete and steel are therefore the most critical materials to consider. The proposed framework does not exclude other materials; the limitations of the case study in Singapore arise from a lack of available data on those materials. Nevertheless, this framework can be easily adapted to other regions with access to high-quality data on various materials. Consequently, the limitations of the study include the absence of consideration for a wide variety of materials, and reliance on process data and MIFs rather than actual bill of material quantities. This approach overlooks the geometry of the building.

In addition, the use of archetype interpolation to model buildings introduces further uncertainty. In multi-criteria decision-making models, one of the methods to test the uncertainty of results is by introducing weights to the parameters. The parameter reliability assessments were conducted with a 13.95% error rate of P1 (embodied GHG emissions). This error creates a fluctuation of up to 0.3 in the total PRMB values (as shown in Fig. A.3). This uncertainty can grow with a higher error rate of the parameters and more weightage applied on top of it. Uncertainty can be reduced with the introduction of highly accurate material information. Furthermore, the truncation error related to the P-LCI approach can be addressed by reiterating the study with hybrid data that considers environmental impacts beyond system boundaries.

This study emphasises the need for local data on materials used in buildings, including their intensity, flow, and embodied factors, as well as information on regional grid emission factors, annual energy demand of buildings, GFA, and the year of construction of individual buildings. The absence of the aforementioned data can lead to discrepancies and averaging of estimates that undermine the robustness of the building GHG emissions assessment process.

Max-Min normalisation is used to bring three parameters to the same scale using a sigmoid function for the purpose of parameter aggregation. It is important to note that if the data contains extreme outliers, Max-Min normalisation can skew the results. In such cases, techniques such as Z-score normalisation or logarithmic normalisation might be more suitable. For nonlinear relationships, other normalisation methods may better reflect the underlying significance of differences between values. For decision problems with three parameters using the SAW method, Max-Min normalisation is generally a strong choice because of its simplicity, interpretability, and effectiveness in small, well-behaved datasets.

5. Conclusions and future work

Despite the high rate of recycling of demolished building materials, the new construction of public residential buildings is highly reliant on imported cement and steel for building their precast structural elements. Nonetheless, our study considers material reuse scenarios in the future with sustainable approaches introduced to new construction.

Potential recyclable materials in buildings (PRMB) are analysed utilising a city-wide whole life carbon assessment developed in this article. The analysis considers three parameters to deliver results that indicate potential recyclable materials in buildings. In the case of the decommissioning of a building, it indicates the material availability for new construction for a given timescale. PRMB analysis as a sustainability metric can help policymakers, resource portfolio managers and other relevant decision-makers to strategise around the global challenge of ageing infrastructure and resource scarcity.

The current processes in the building construction sector are far behind in being circular and lack a holistic approach towards achieving sustainability. Efficient recycling and reusability of materials from construction and demolition processes can be improved with long-term scenario planning utilising digital tools. The PRMB framework proposed in this article can be applied to cities around the world to understand opportunities for potential recyclable materials in buildings. The scenarios on top of the PRMB results can explore sustainable practices and circular approaches towards building demolition.

The application can provide a digital tool to support the tracking and management of potentially recyclable materials and reuse scenarios in new building construction. Our future work will focus on analysing how new developments can be planned along with their construction material needs using circular approaches in construction.

CRediT authorship contribution statement

Pradeep Alva: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Riccardo Talami:** Writing – original draft, Methodology, Formal analysis, Data curation. **Wanyu Pei:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Goran Sibenik:** Writing – review & editing. **Martín Mosteiro-Romero:** Writing – review & editing. **Clayton Miller:** Writing – review & editing, Supervision. **Rudi Stouffs:** Writing – review & editing, Supervision, Resources.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rudi Stouffs reports financial support was provided by National Research Foundation Singapore. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Figs. A.1–A.3.

Data availability

Data will be made available on request.

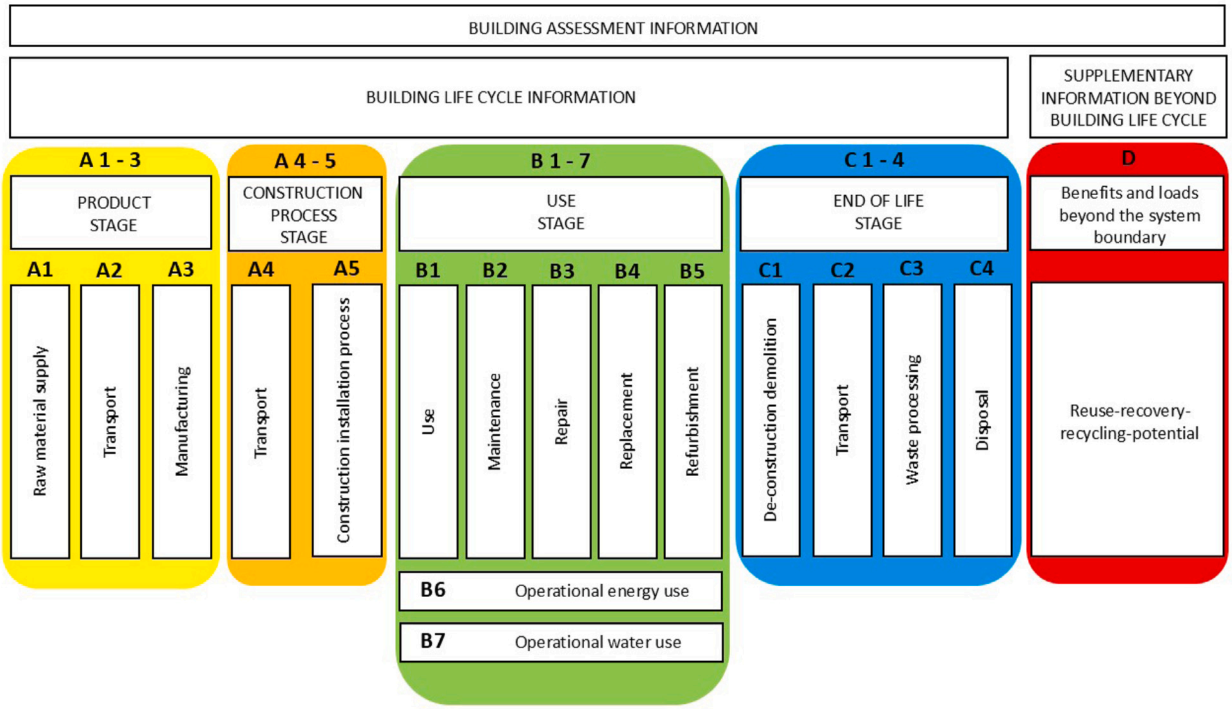

Fig. A.1. Modular information of the various stages of building assessment. Note: Modules *B1* to *B7* are considered as the use stage of the building LCA. Module *B6* represents the operational GHG emissions, i.e. emissions resulting from energy use to operate the building.
Source: European Standard (2021) BS EN 15804:2012+A2:2019, European Standard (2011) BS EN 15978:2011, and World Green Building Council (2019) (WorldGBC)

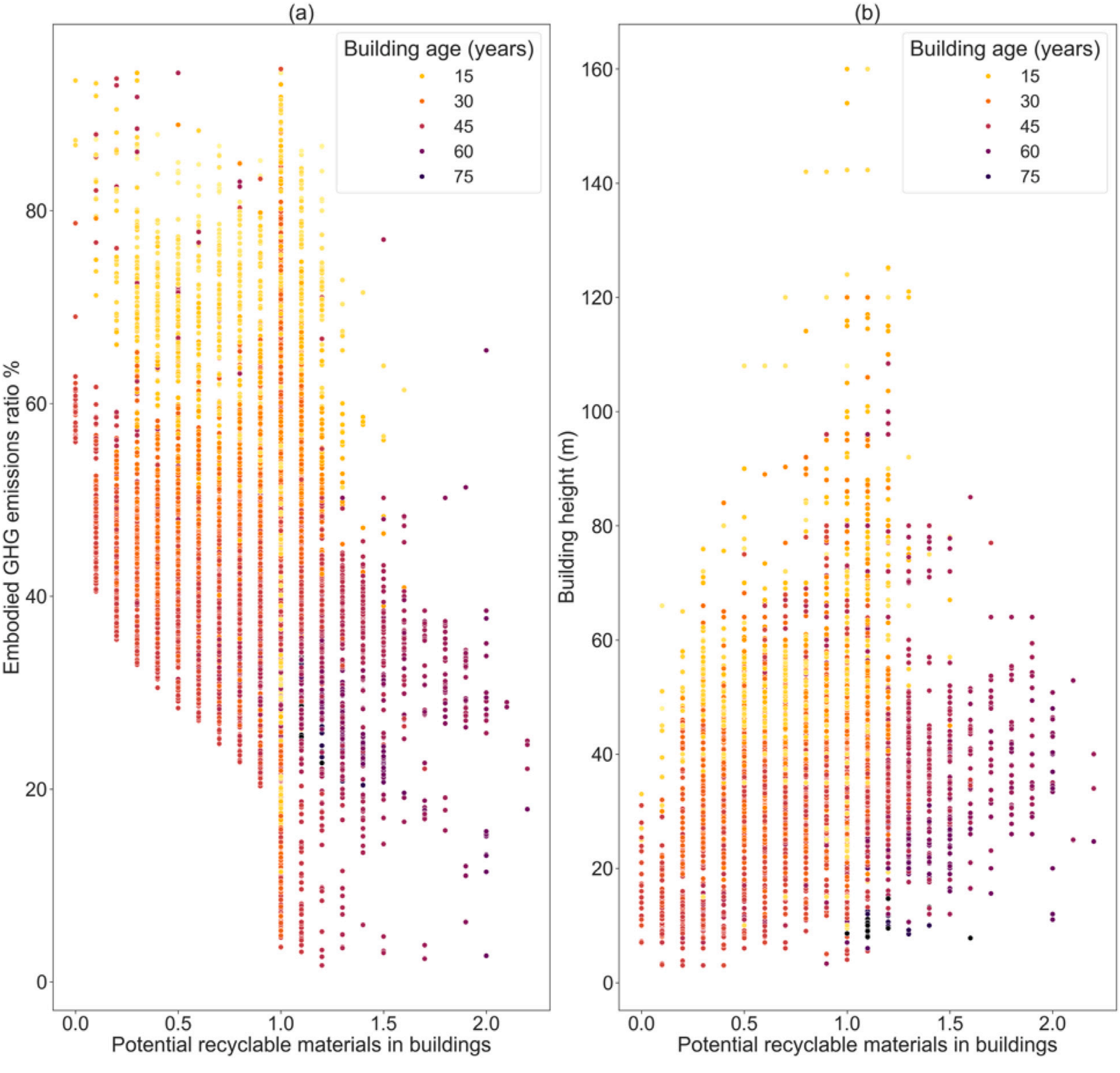

Fig. A.2. A comparison of PRMB results (x-axis) with (a) upfront embodied GHG emissions ratio and (b) building height (in y-axes).

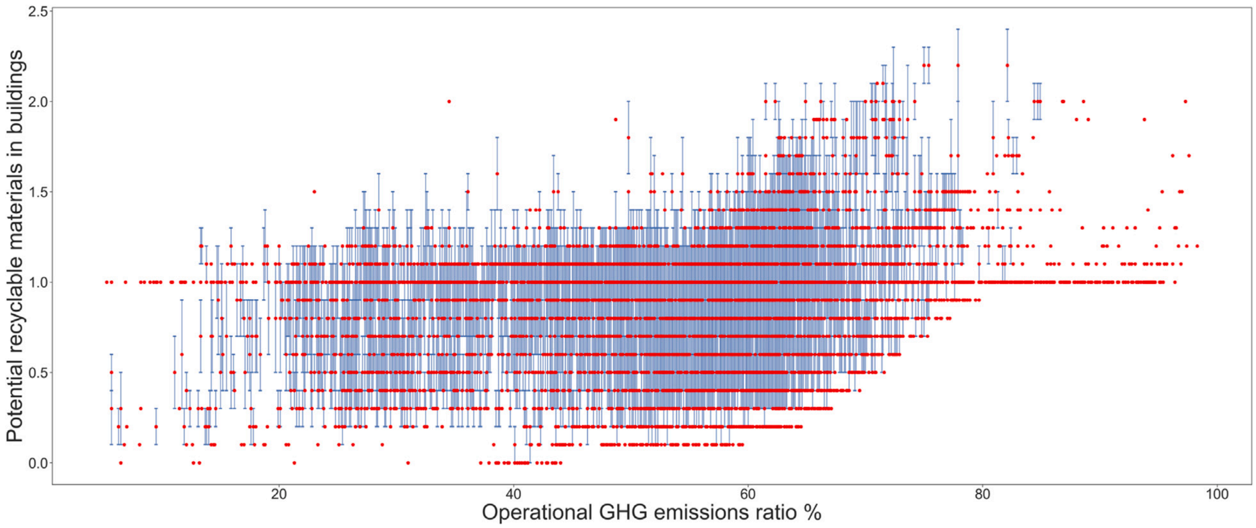

Fig. A.3. A comparison of operational GHG emissions ratio (x-axis) and PRMB results (y-axis) with error bars.

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