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Title:
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Date:
2025-12-03

Citation:
Torres Salazar, C., Crawford, R. H., Stojanovic, D. & Helal, J. (2025). Advancing housing retrofit: A framework for early-stage evaluation of material circularity, lifecycle emissions, and energy performance. Proceedings of the 58th International Conference of the Architectural Science Association, pp.116-125. The Architectural Science Association (ANZAScA). https://doi.org/10.65388/onoi3754.

Persistent Link:
https://hdl.handle.net/11343/364670

C. Torres Salazar, R. H. Crawford, D. Stojanovic and J. Helal (2025). Advancing housing retrofit: A framework for early-stage evaluation of material circularity, lifecycle emissions, and energy performance. In R.H. Crawford, A. Stephan, C. Candido, J. Helal and P. Gobinath (eds.), Proceedings of the *58th International Conference of the Architectural Science Association 2025*, pp. 116-125. ©2025, The Architectural Science Association and The University of Melbourne, Australia. https://doi.org/10.65388/ONOI3754

Advancing housing retrofit: A framework for early-stage evaluation of material circularity, lifecycle emissions, and energy performance

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Abstract: National frameworks for new buildings increasingly address operational energy and, in some cases, lifecycle greenhouse gas (GHG) emissions, yet comparable requirements for retrofits remain rare. In many contexts, retrofit projects proceed without efficiency targets, lifecycle GHG benchmarks, or consideration of material circularity. This gap is significant, but the value of such indicators extends beyond compliance. When used as design tools, they enable architects, engineers, and environmental designers to compare strategies, anticipate trade-offs, and integrate sustainability into early decisions. Retrofitting is particularly relevant in this context, as it reduces GHG emissions by extending the lifespan of existing housing and minimising the impacts of new construction. Despite this potential, most retrofit evaluations prioritise operational performance while overlooking wider lifecycle GHG impacts. Lifecycle assessment (LCA) can quantify embodied and end-of-life emissions, yet these phases are often excluded due to uncertainty and limited data at early stages. Retrofit studies emphasise the importance of material-related emissions and often consider cost factors, such as upfront investment and payback periods, but they rarely integrate circularity considerations. Recent work has begun to apply material circularity indicators, showing their potential to reveal trade-offs with GHG emissions. Building on these advances, this study presents an integrated framework that combines material circularity, lifecycle GHG emissions, and energy performance to support comparative evaluation of retrofit strategies. The framework is intended not only to address gaps in assessment practice but also to enrich design by making the environmental consequences of material and component choices explicit for practitioners. While adaptable to diverse contexts, it is applied here to the Australian multi-residential sector, which offers major opportunities for scalable emission reductions.

Keywords: Residential retrofit, lifecycle assessment, material circularity, decision support.

1. Introduction

The construction and building sector is a major contributor to global environmental impacts, accounting for about 38 per cent of global carbon dioxide (CO_2) emissions and 35 per cent of total energy consumption (UNEP, 2020). In 2021, it was also responsible for 30-40% of total solid waste generation (Eurostat, 2021). These impacts are largely driven by the production and use of carbon-intensive materials such as cement and steel (IPCC, 2023). Within the sector, residential buildings account for roughly 70% of energy demand (IPCC, 2023), with a significant share of emissions already embedded in the existing housing stock, particularly in contexts such as Australia. Taken together, these figures underscore the critical importance of the building sector in achieving the transition to a low-carbon and circular economy.

In recent years, national regulations have begun to extend performance requirements beyond operational energy. For example, the French RE2020 framework establishes benchmarks for lifecycle GHG emissions in new residential construction, while in Australia, the Nationwide House Energy Rating Scheme (NatHERS) has increased its baseline from 5 to 7 stars for new dwellings. However, retrofits are not subject to comparable requirements. Interventions that affect less than half of the building fabric are exempt from NatHERS, and embodied emissions and material circularity remain largely outside the scope of regulation. This gap is significant given that much of the Australian housing stock was constructed before the introduction of energy performance

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standards—more than 96% of dwellings in Greater Melbourne were built prior to the 5-star requirement in 2005 (Seo et al., 2018)—and many continue to rely on fossil fuel-based heating systems. As a result, major impacts associated with material sourcing, manufacturing, and end-of-life processes remain insufficiently addressed. In this study, the term residential energy retrofit refers to the upgrade of an existing residential building through interventions that reduce energy consumption for heating and cooling. The strategies considered here are building fabric-focused, including improvements to the thermal envelope and material systems.

Decarbonisation efforts in the built environment have traditionally prioritised operational energy efficiency; however, there is increasing recognition of the need to address embodied emissions. Embodied emissions arise from material production, transport, construction, maintenance, and disposal. In new high-performance buildings, they can account for 45–50% of total lifecycle emissions (GBCA and Thinkstep ANZ 2021), and projections for Australia suggest that without targeted strategies, they could rise to 85% of building-related emissions by 2050. This trend is reinforced by the progressive decarbonisation of the electricity grid, which reduces the relative contribution of operational energy and makes material-related impacts more significant. The same dynamic applies to retrofit projects: while energy upgrades reduce operational demand, they also introduce additional embodied emissions through the use of new materials and components. Compared to demolition and new construction, however, retrofitting remains a resource-efficient strategy that avoids the full embodied cost of replacement and can further limit emissions when low-impact or circular materials are selected. Common interventions include improvements to the thermal envelope, window and HVAC upgrades, and the substitution of conventional products with lower-carbon alternatives. Despite this potential, current practice remains narrowly focused on operational efficiency, with limited attention to lifecycle impacts or the circularity potential of materials (Stephan & Athanassiadis, 2018).

The circular economy (CE) provides a complementary framework for addressing the broader environmental impacts of buildings. It is defined here as a systematic approach to resource use that follows a hierarchy of refusal, reduction, reuse, repair, remanufacture, recycling, and recovery (Ellen MacArthur Foundation 2019). Applied to retrofitting, CE emphasises extending the service life of existing structures, enabling the recovery of materials, and reducing reliance on virgin resources. Strategies include not only reversible design and connections but also material efficiency, adaptability, and the alignment of component service lives. In practice, however, implementing CE principles in retrofit projects remains challenging. Conventional external insulation systems, for example, often employ adhesive-based solutions that hinder disassembly and reuse, whereas circular retrofit strategies apply reversible mechanical connections and design for disassembly to extend material lifecycles (Haas et al., 2015). Despite such emerging examples, widespread adoption is still constrained by regulatory, economic, and informational barriers.

Life Cycle Assessment (LCA) and the Material Circularity Indicator (MCI) are established methods for evaluating environmental performance across the building lifecycle, including greenhouse gas emissions, energy use, and material flows. However, both face limitations when applied to retrofit contexts, particularly at early stages of design. LCA can quantify both embodied and operational emissions, but it struggles to address circularity due to the uncertainty and high context-specificity of end-of-life scenarios. The MCI offers a complementary perspective by evaluating the degree of material circularity, taking into account the proportion of virgin feedstock in inputs, the utility of materials in use, and their potential for reuse or recycling at the end of their life. It was originally developed at the product scale, but it can also be applied at the building level through a bottom-up analysis of components and assemblies, an approach that provides a more comprehensive picture of retrofit performance. In practice, however, both methods are usually employed after major design decisions have been made, which limits their capacity to influence material selection and construction strategies. More broadly, existing energy rating schemes also concentrate on operational efficiency while giving limited attention to embodied emissions and circularity. This fragmented methodological landscape highlights a critical gap in current practice: the absence of integrated design-stage frameworks that enable a comparative and comprehensive evaluation of retrofit strategies.

The motivation for addressing this gap extends beyond refining assessment methods or creating new regulatory tools. The framework is intended as a resource for design practice, enabling architects, engineers, and environmental designers to anticipate the environmental consequences of their choices and integrate this knowledge into the design process. By foregrounding environmental indicators in early decisions, it supports more sustainable strategies rather than additional compliance calculations. The study makes four principal contributions: it unifies the evaluation of lifecycle greenhouse gas emissions, material circularity, and operational energy performance; it incorporates the Material Circularity Indicator as a complement to LCA, extending assessment to include material origin, utility, and recovery potential; it develops a comparative workflow that makes trade offs between indicators explicit through multi chord visualisation; and it situates the analysis in the multi residential housing sector in Australia, a context underexamined despite its significance for emission reduction and circularity.

1.1. Aim

This paper proposes an integrated framework to support early-stage decision-making in residential energy retrofit, focusing on lifecycle greenhouse gas (GHG) emissions, material circularity, and energy performance.

2. Background

2.1. Scope

This paper examines approaches to evaluating residential energy retrofits, with a specific focus on lifecycle emissions, material circularity, and operational energy performance. The review highlights recurring gaps in these domains, which inform the framework proposed in Section 3. The framework is then discussed in terms of its potential applications, limitations, and future development.

2.2. Environmental assessment methods at early stages

Environmental assessment tools are essential for evaluating the performance of retrofit strategies, but their application at early design stages remains limited. Life Cycle Assessment (LCA) is a well-established method for quantifying environmental impacts across a building lifecycle. It enables the evaluation of both embodied and operational emissions, and is central to whole-of-life carbon accounting. In retrofit contexts, LCA can help assess the environmental implications of material replacement, retention, or efficiency upgrades. However, LCA is often applied retrospectively, after major design decisions have already been made. This limits its influence on early design thinking. Cabeza et al. (2014) and Lam et al. (2022) note that existing LCA tools typically require detailed inputs that are not available in conceptual stages and are poorly aligned with architectural workflows. Simplified or phased methods have been proposed to address these issues, offering comparative feedback earlier in the process (Prideaux et al., 2024).

To address long-term material impacts that LCA may overlook, particularly those beyond the system boundary, complementary tools such as the Material Circularity Indicator (MCI) have been developed. The MCI, introduced by the Ellen MacArthur Foundation (2019), measures the extent to which materials are recycled, reused, or recovered at the end of their life cycle. While useful in principle, the MCI has seen limited application in design practice due to its focus on product-level data and limited integration with building-scale assessment workflows. Tools based on digital modelling platforms, including Building Information Modelling (BIM), offer some potential, but challenges with interoperability and data consistency remain significant barriers (Obrecht et al., 2020).

More broadly, existing environmental assessment tools tend to address one aspect of sustainability, such as operational energy, lifecycle emissions, or circularity, in isolation. This fragmentation makes it challenging to compare retrofit scenarios across multiple environmental dimensions. Few frameworks support a combined approach that can inform early-stage design by revealing trade-offs and complementarities between thermal performance, environmental impact, and material circularity.

2.3. Lifecycle emissions in retrofit decision-making

Retrofitting existing buildings plays a central role in global decarbonisation efforts, particularly in light of the substantial environmental burden posed by the built environment. Globally, buildings are responsible for over 40 % of carbon dioxide emissions (Galimshina et al., 2024), with emissions arising from both operational and embodied sources. While operational energy use for heating, cooling, and electricity has traditionally been the primary target of retrofit policies, the embodied emissions associated with building materials and processes have emerged as a critical area of concern. These impacts include emissions generated during material extraction, manufacturing, transport, and end-of-life processing.

Embodied emissions can represent 20 to 25 per cent of total lifecycle emissions in standard buildings, but this proportion increases significantly in energy-efficient or low-carbon buildings. Studies show that it can reach 45 to 50%, and in some cases, even exceed 90% of total emissions (Rock et al., 2020). As operational energy demands decrease through performance upgrades or the decarbonization of electricity grids, embodied carbon becomes a dominant share of total life-cycle emissions. Consequently, retrofit interventions that rely on high-impact materials may shift the environmental burden from the operational phase to earlier stages of the lifecycle.

Sicignano et al. (2019) and Asdrubali et al. (2019) demonstrate how deep energy retrofits can reduce operational energy use but increase embodied impacts due to the addition of construction layers, insulation, or composite materials. Lausselet et al. (2020) argue that without improvements in material efficiency, retrofits may offer diminishing environmental returns. This concern is particularly relevant in the Australian context, where typical residential buildings, such as brick veneer and weatherboard houses, often lack thermal efficiency and require substantial material interventions to meet updated performance standards (Li et al., 2022).

To comprehensively evaluate the impacts of retrofitting, it is necessary to consider all relevant lifecycle stages. These include production (A1 to A3), transport and installation (A4 to A5), maintenance and replacement (B4), refurbishment (B5), and end-of-life processing (C1 to C4), as defined by EN 15978 and RICS 2017 guidelines. Examples, such as the Belgian MMG methodology (Allacker et al., 2013), demonstrate how renovation measures can be assessed across all stages, thereby ensuring that environmental improvements in one phase do not lead to increased impacts in another. The concept of refurbishment is typically included in Stage B5 and refers to planned interventions that improve the function or performance of a building during its service life. This study frames retrofit strategies accordingly, encompassing material replacement, enhancement, and performance extension within a lifecycle-based accounting structure.

2.4. Material circularity indicators and their complementary potential in retrofit evaluation

Alongside carbon mitigation, material circularity has gained prominence as a framework for improving resource efficiency in the built environment. Unlike linear models of take, make, and dispose, circularity seeks to extend the service life of materials and reduce resource extraction through strategies that enable disassembly, recycling, and adaptive reuse. In retrofit contexts, this involves selecting materials and construction systems that can be recovered, reassembled, or reconfigured at the end of their use phase (De Wolf et al., 2020). Yet despite growing policy and academic interest, circularity remains underutilised in practice, particularly in building retrofits. Galimshina et al. (2024) highlight the continued reliance on cost-driven, fossil fuel-based materials in renovation projects, which undermines both lifecycle and circularity objectives. Moreover, construction practices often involve irreversible connections, adhesive-based fixings, and composite layers that hinder disassembly and recycling, increasing waste and complicating environmental assessment.

Recent research has proposed a range of methods to embed circularity within design workflows. Hartwell and Overend (2024) introduce the Reclamation Potential metric, which evaluates ease of disassembly, material longevity, and recovery opportunities at the end of a product's life. This perspective highlights that circularity depends not only on material properties but also on assembly logic, coordination of service lives, and deconstruction planning. Yet these considerations remain largely absent from mainstream design practice and regulatory frameworks. Conventional LCA methods, such as EN 15978, further exacerbate this gap by calculating material replacements solely based on service life, without considering interdependencies between components. Consequently, such approaches cannot capture the benefits of strategies like design for disassembly and reuse (Vandervaeren et al., 2020). Reversible building design offers a complementary perspective by foregrounding strategies that maintain the recovery potential of components across the design process. Durmisevic (2018) identifies three levels of dependency—functional, technical, and physical—that influence the degree of reversibility. Functional decomposition and systematisation are central during early design phases, while life cycle coordination, technical composition, and connection typologies determine whether components can ultimately be recovered without damage. Taken together, these insights demonstrate the need to complement conventional LCA with indicators that explicitly account for material origin, utility, and recovery potential.

Several indicators have been developed to evaluate circularity at the building scale. The Material Circularity Indicator (MCI), introduced by the Ellen MacArthur Foundation (2019), provides a baseline assessment of circular performance by considering material origin, recovery potential, and utility, while the Building Circularity Indicator (BCI), developed by Alba Concepts, extends this approach with greater attention to connection types, adaptability, and construction reversibility. Although the BCI offers a more comprehensive and retrofit-relevant framework, it has not yet achieved widespread adoption and remains primarily used in research and pilot studies. For such indicators to inform practice, they must be embedded into early design workflows through scenario modelling, visualisation strategies, and component-level analysis. Recent studies demonstrate that coupling circularity indicators with parametric or digital modelling environments can facilitate iterative design exploration; however, the application remains constrained by inconsistent data, the absence of standardised metrics, and limited integration with established lifecycle methods, such as LCA. Since conventional LCA typically excludes downstream material impacts, circularity indicators provide a necessary complement by capturing end-of-life scenarios and the long-term utility of resources. Integrating these with emissions and energy assessments is therefore essential for developing more comprehensive and comparative evaluations of retrofit strategies.

2.5. Broader limitations in retrofit evaluation: energy, typology and decision support

The residential sector is central to climate mitigation, particularly in Australia, where a significant portion of the housing stock predates energy performance standards. In Greater Melbourne, for example, more than 96% of dwellings were constructed before the introduction of the five-star NatHERS requirement in 2005 (Seo et al., 2018). Although recent regulatory changes, such as the shift to seven-star NatHERS ratings, have advanced operational performance, they remain narrowly focused on occupancy energy demand, leaving embodied emissions and material circularity largely unaddressed in both policy and practice (Stephan & Athanassiadis, 2018). Retrofit research in Australia has similarly concentrated on detached and semi-detached dwellings, while multi-residential buildings remain underexamined despite their growing urban significance and their distinct regulatory, spatial, and construction challenges, particularly in relation to façade upgrades, access, and tenancy coordination (Galimshina et al., 2024; Islam et al., 2022). Moreover, existing evaluations often prioritise operational performance and embodied impacts without enabling explicit comparison across strategies. Multi-criteria approaches, as demonstrated by Rajagopalan et al. (2021), highlight how outcomes can vary according to user priorities; however, these methods remain marginal in practice. Without tools that make the consequences of prioritising one objective over another. For example, reducing energy demand at the expense of circularity, decision-making in early design stages remains fragmented.

2.6. Research gap

Although interest in sustainable retrofit strategies continues to grow, three key limitations remain in current research and practice. First, existing studies rarely integrate circularity indicators that complement conventional lifecycle assessment. While most assessments emphasise operational and embodied emissions within stages A to C, relatively few capture upstream aspects, such as the origin of input materials, or downstream outcomes, including reuse, recycling, or recovery. This omission means that the long-term value of circular strategies is often underrepresented. Second, methods for trade-off analysis remain limited. While individual metrics are commonly reported, few approaches explicitly compare outcomes across strategies. Existing visualisation tools can combine metrics, but they rarely show how one decision, such as improving energy performance, may simultaneously increase embodied impacts or reduce circularity, thereby limiting their value for early design decision-making. Third, multi-residential retrofits in Australia are underrepresented in the literature. Despite some industry and non-profit guidance, academic evaluations remain scarce, even though these buildings present distinct regulatory, spatial, and construction challenges that require dedicated investigation.

3. Framework for assessing material circularity, lifecycle GHG, and energy performance of energy retrofit strategies

This study proposes an integrated framework for evaluating residential retrofit strategies across three environmental indicators: material circularity, lifecycle greenhouse gas emissions, and operational energy performance. The framework is designed to facilitate early-stage decision-making by making trade-offs and synergies between these dimensions explicit, without reducing them to a single score. Following the distinction introduced by Crawford and Xadorel (2017), the framework is presented through two layers: embedded elements, which define a replicable methodological structure, and project-specific applications, which reflect the unique characteristics of the case examined here. These are summarised in Table 1, which illustrates both the general workflow and its operationalisation in the context of Australian multi-residential retrofits.

3.1. Embedded framework elements (conceptual structure)

The embedded layer of the framework defines a replicable methodological structure that can be applied across retrofit contexts. It comprises eight steps, moving from scope definition and baseline characterisation to scenario testing, trade-off analysis, and decision support. Together, these steps provide a systematic process for embedding lifecycle emissions, material circularity, and energy performance into early design evaluation.

- *Step 1. Scope and objectives*
  Define system boundaries and performance objectives. These choices determine which impacts are captured and ensure relevance for early design decisions.
- *Step 2. Baseline characterisation*

Establish a reference building, documenting typology, construction, and current performance as the counterfactual against which retrofit options are assessed.

- *Step 3. Evaluation metrics*
  Adopt three independent indicators—lifecycle GHG emissions, material circularity, and operational energy performance—to capture distinct sustainability dimensions.
- *Step 4. Retrofit strategy definition*
  Structure interventions as parameterised envelope strategies (airtightness, insulation, glazing, shading, thermal bridges, combined packages, and circularity-led approaches), enabling systematic and comparative evaluation.
- *Step 5. Scenario modelling*
  Apply each strategy to the baseline using consistent methods, allowing exploration of how interventions, individually or in combination, influence outcomes.
- *Step 6. Comparative analysis*
  Compile and visualise results (bar charts, matrices, multichord diagrams) to make synergies and conflicts explicit without reducing them to a single index.
- *Step 7. Sensitivity testing*
  Assess robustness by varying climate contexts and key parameters, identifying which assumptions have the most significant influence on outcomes.
- Step 8. Decision support outputs
  Present results in a comparative format that supports interpretation by designers and stakeholders, embedding lifecycle and circularity considerations into early retrofit planning without imposing prescriptive rankings.

These eight elements form the embedded structure of the framework. Their correspondence with the project-specific application is summarised in Table 1, which presents the general workflow alongside its operationalisation for Australian multi-residential retrofits.

Table 1. Integrated framework for evaluating residential retrofit strategies. (source: Author,2025)

Embedded framework (replicable workflow)	**Project-specific application**
1. Definition of scope and objectives – The framework begins with the specification of system boundaries and performance indicators to guide early-stage evaluation.	The scope encompasses whole-of-life impacts (stages A through C). Comparative anchors are established for operational energy, embodied emissions, and material circularity to facilitate a systematic evaluation of retrofit scenarios.
2. Baseline characterisation – The existing building is documented as a reference case against which interventions are evaluated.	A representative multi-residential archetype with brick veneer construction is adopted as the baseline, reflecting its dominance in Australian post-war housing and its relevance for large-scale retrofit opportunities (Seo et al., 2018). Embodied impacts already incurred are treated as fixed, with retrofit evaluation focusing on the marginal impacts of interventions relative to this reference case.
3. Selection of evaluation metrics – Independent indicators are identified to capture environmental and energy performance dimensions.	Three indicators are applied: operational energy, assessed with NatHERS using a 7-star benchmark as the principal reference; embodied emissions, compared against indicative reduction targets of 40, 60, and 80% relative to baseline, aligned with national decarbonisation plans; and material circularity, evaluated with the MCI using thresholds of 0.25, 0.50, and 0.75 to represent low, medium, and high circularity. These benchmarks serve as comparative anchors for interpreting performance.

4. Definition of retrofit strategies – Targeted envelope interventions are identified and parameterised for comparative testing.	For the proof of concept, a limited set of envelope strategies is modelled independently to demonstrate the workflow. These include: • Airtightness: variation in air leakage rate (ACH50). • Insulation: thickness and placement in roof and wall assemblies. • Glazing: U-value and SHGC, tested as paired specifications. • Shading: overhang ratio by façade orientation, converted to a shading coefficient (SC). • Thermal bridges: catalogue ψ-values for key junctions (slab edge, roof–wall, window reveal), with outputs reported as (W/K) and estimated changes in heating demand.
5. Scenario modelling – Each strategy is applied to the baseline using consistent assessment protocols to ensure comparability.	Each strategy is applied independently to the baseline building using consistent protocols, producing a compact set of approximately ten cases across two climates (Melbourne, temperate; Brisbane, warm humid). This restricted scope demonstrates the comparative functionality of the framework without requiring full combinatorial modelling.
6. Comparative analysis – Results are compiled and examined to identify synergies and trade-offs across indicators, using visualisation to make relationships explicit without aggregation.	In Figure 1, each chord represents one assembly-level intervention: airtightness; insulation to roof and walls shown as separate chords; glazing; shading via SC; thermal bridges.
7. Sensitivity testing – Robustness is assessed by examining the influence of climatic variation and parameter assumptions.	Robustness is examined through both climate and parameter variation. Scenarios are modelled for Melbourne (temperate) and Brisbane (warm, humid), while key parameters such as airtightness (ACH50), insulation thickness and placement, glazing U-value and SHGC, shading overhang ratio (converted to SC), and ψ-values for thermal bridges are systematically varied. The existing building is treated as a fixed baseline, with retrofit impacts calculated only for new materials and interventions. In Figure 1, parameter variants are represented in light grey.
8. Decision-support outputs – Results are presented to facilitate project-specific interpretation without prescriptive weighting.	Outputs converge on the three indicators: lifecycle GHG emissions, NatHERS ratings, and MCI scores, with assembly-level comparisons.

Table 1 summarises the framework as both a generalisable structure and a case-specific application. To illustrate how comparative results can be communicated within this workflow, Figure 1 presents the multichord visualisation adopted in this study. This technique was selected because it allows individual retrofit strategies, such as airtightness, insulation, glazing, shading devices, or thermal bridge reductions, to be represented as distinct chords while linking them simultaneously to the three assessment indicators. By structuring the diagram in this way, the influence of each strategy can be examined independently, while still recognising the potential for strategies to be combined in practice. Compared with conventional bar charts or matrices, the multichord format highlights both the direction and relative intensity of relationships, making trade-offs and synergies between lifecycle GHG emissions, operational energy performance, and material circularity more readily interpretable.

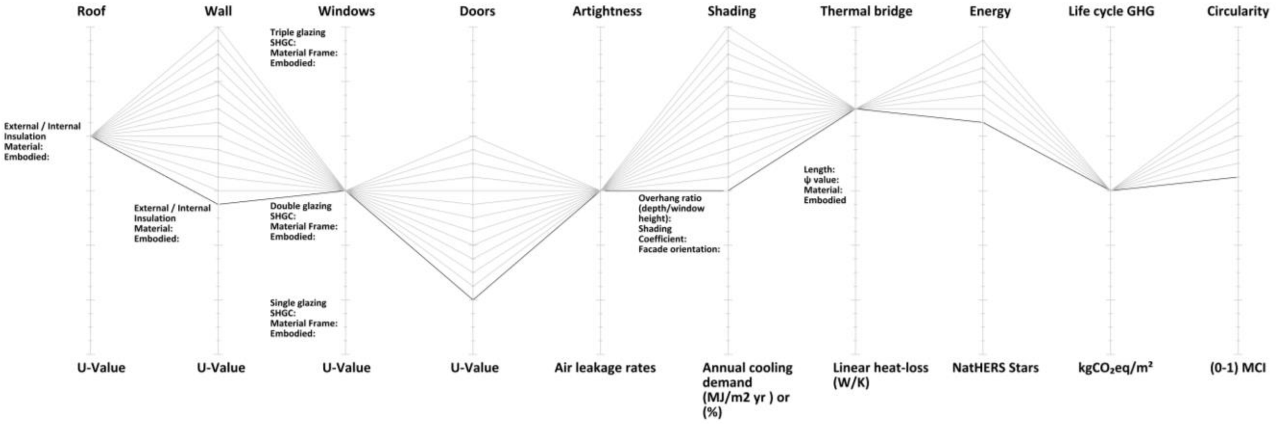

Figure 1. Example of multichord visualisation illustrating the relationship between retrofit decisions (source: Author, 2025).

3.2. Project-based information (context-specific application)

The framework is applied to a representative multi-residential archetype with brick veneer construction, reflecting its prevalence in Australian post-war housing and its relevance for large-scale retrofit opportunities (Seo et al., 2018). The assessment considers whole-of-life impacts (stages A to C), treating embodied impacts already incurred as fixed and focusing on the marginal effects of retrofit interventions. Three indicators are used as comparative anchors: operational energy, embodied emissions, and material circularity, each assessed against indicative benchmarks to support systematic comparison. To demonstrate proof of concept, a selected set of envelope strategies is modelled independently, covering airtightness, insulation, glazing, shading, and thermal bridges. Scenarios are tested in two climate contexts, temperate and warm humid, with parameter variations applied to examine robustness. As illustrated in Figure 1, results are presented at the assembly level, with parameter variants shown in light grey. Outputs converge on the three indicators to highlight trade-offs and synergies relevant to early design decision-making.

4. Discussion and conclusion

4.1. Significance of the framework

This paper has presented the conceptual design of an integrated framework for evaluating residential retrofit strategies across material circularity, lifecycle greenhouse gas emissions, and operational energy performance. The framework is designed to facilitate early-stage decision-making by enabling a transparent comparison of environmental criteria that are often assessed in isolation. Its modular structure and side-by-side outputs allow users to identify trade-offs and align retrofit choices with project-specific priorities and regulatory contexts. The contribution lies in addressing key gaps in current practice: the limited integration of circularity into retrofit evaluation, the restricted treatment of downstream impacts beyond Stage C, and the absence of visual tools that make trade-offs between strategies explicit. In doing so, the framework establishes a foundation for structured, scenario-based exploration of retrofit interventions at the component level, with potential to inform both research and design practice.

4.2. Limitations and scope

At this stage the framework remains conceptual and has not yet been tested through numerical modelling or applied to case studies, meaning that no scenario results are presented in this paper. While the assessment structure has been defined, the selection of specific LCA databases, emission factors, and modelling tools will be determined in future applications. Uncertainties inherent to retrofit contexts, such as the age and composition of existing materials or differences in historical production processes, are acknowledged but not yet quantified. The Material Circularity Indicator (MCI) is included as a complementary metric; however, in its current application it captures potential rather than realised material recovery, a distinction that will be refined in subsequent work. The scope is intentionally restricted to indicators that can be applied meaningfully at the early design stage, namely lifecycle greenhouse gas emissions, material circularity, and operational energy, while more detailed aspects such as hygrothermal behaviour are excluded, as these depend on material moisture transport and long term interactions between assemblies and climate that are better addressed in later design phases or with specialised simulation tools. Finally, although the framework prioritises transparency by presenting disaggregated outputs and avoiding aggregation, it does not yet provide simplified practitioner oriented metrics or integrate economic indicators, both of which often dominate real world decision making. These limitations highlight directions for refinement in future research, including empirical testing, the incorporation of expanded datasets, and practitioner engagement to align outputs more closely with design workflows.

4.3. Next steps

The next phase of this research will test the framework by applying it to a representative multi-residential building. Planned tasks include modelling targeted retrofit scenarios, compiling data on materials and assemblies, and applying lifecycle and energy simulations across different climate zones. Sensitivity testing will be used to explore uncertainties in building stock and material assumptions, while practitioner workshops will assess the clarity and usability of the visualisation strategy, including the potential for simplified indicators. The framework also holds potential for adaptation to other building types, including detached dwellings, commercial buildings, and public housing, given its modular and comparative structure.

5. Acknowledgements

This research forms part of a doctoral study supported by a research grant. The authors acknowledge the contributions of advisory input and methodological feedback that informed the development of the visualisation approach and overall research design.

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