

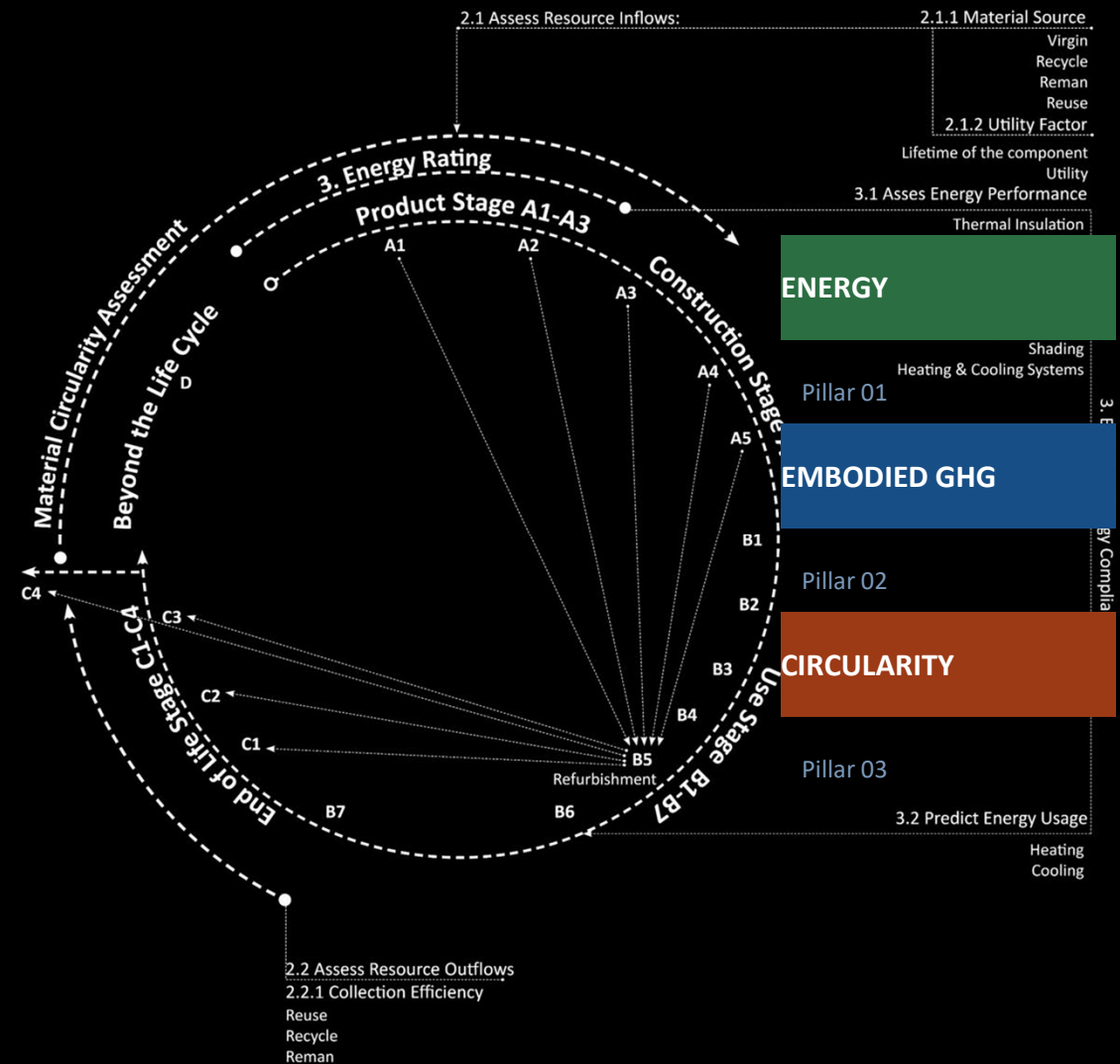
# Advancing housing retrofit:

An Integrated Assessment Framework for Operational Energy, Embodied GHG, and Material Circularity in Australian Multi-Residential Buildings

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## SECTION 1: SCOPE & PROBLEM FRAMING

# The Retrofit Paradox

Why doesn't energy compliance alone capture the full GHG picture of a retrofit?

**Australia's housing stock is ageing and energy-inefficient.**

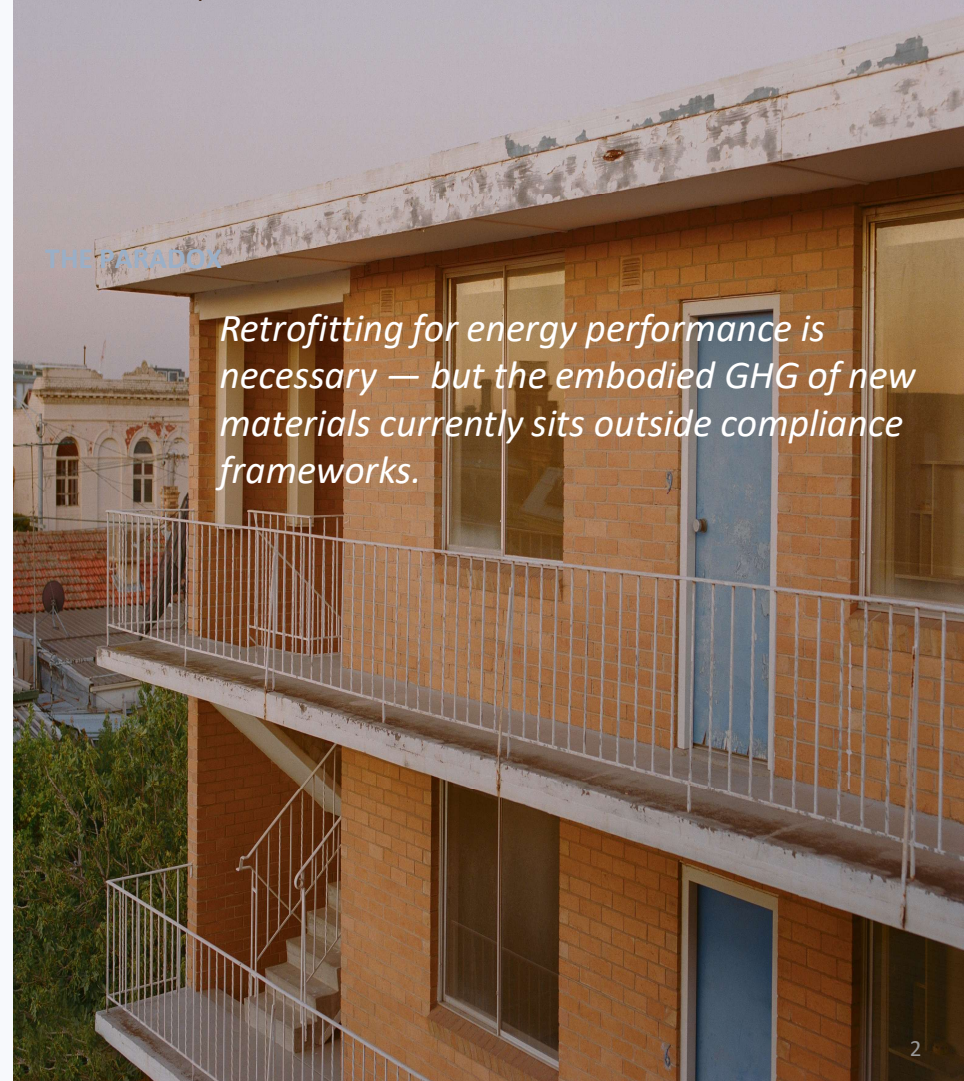
The dominant policy response is mandatory NatHERS compliance: upgrade insulation, windows, and sealing to reach the 7-star threshold.

**The result: an embodied GHG spike at the point of retrofit that, as the grid decarbonises, can take over 20 years to offset — or may never be recovered within the building's service life. (Carvalho et al., 2026)**

**38%** of global CO<sub>2</sub>

From the built environment (IEA, 2022). Retrofits must address both embodied and operational impacts.

Park St  
Photo: Ben Moynihan



## Four Systemic Gaps

A synthesis of the literature reveals four interlocking failures in current retrofit practice

### Metric Gap

#### *Operational vs Embodied*

NatHERS and all Australian rating tools measure only operational energy. Embodied GHG (A1–C4) is absent from compliance pathways. A building that meets 7-star NatHERS may have a net-positive lifecycle embodied GHG impact.

### Typology Gap

#### *Detached vs Multi-Residential*

95% of retrofit literature and all major tools focus on single-family detached housing. Multi-residential buildings differ structurally (party walls, shared services, tenure complexity) and are poorly served by current frameworks.

### Methodology Gap

#### *Linear vs Circular LCA*

Conventional LCA uses a cradle-to-grave linear model. Circular economy retrofit strategies (refurbishment, reuse, biogenic materials) require modules D and C4 to be assessed. No Australian tool handles this.

### Tool Gap

#### *Fragmentation vs Integration*

Energy simulation, LCA, and circularity assessment are performed in separate, incompatible software environments. No single tool integrates all three pillars. This produces incomplete, often contradictory recommendations.

## SECTION 2: LITERATURE REVIEW

# The Tool Fragmentation Gap

No existing tool simultaneously covers all three assessment pillars (Islam et al., 2021; Krarti, 2024; extended for Australian context)

| Tool / URL                                                                       | Focus & Engine                                             | Energy | GHG | Circ. |
|----------------------------------------------------------------------------------|------------------------------------------------------------|--------|-----|-------|
| <b>Consumer-Facing Tools (Adapted from Islam et al., 2021)</b>                   |                                                            |        |     |       |
| B <sup>3</sup> -RETROTOOL<br>(Brussels)                                          | Energy & env. assessment;<br>urban retrofitting (top-down) | ✓      | ✓   | —     |
| DanRETRO<br>(Denmark)                                                            | EnergyPlus-based;<br>envelope, heating, behaviour          | ✓      | ✓   | —     |
| CAALAcAala<br>(Germany)                                                          | Real-time LCA feedback;<br>early design phase              | ✓      | ✓   | —     |
| MyHomeEQ<br>(USA)                                                                | Municipal data; EQ score;<br>envelope & cooling            | ✓      | —   | —     |
| <b>Expert Platforms (Adapted from Krarti, 2024; Cervantes Puma et al., 2024)</b> |                                                            |        |     |       |
| OneClick LCA /<br>EC3                                                            | Embodied GHG; BIM-<br>integrated; EPD-based                | —      | ✓   | —     |
| EnergyPlus /<br>IES VE                                                           | Operational LCA; high-<br>fidelity simulation              | ✓      | ~   | —     |
| EMF Tool /<br>C-Calc                                                             | Official MCI calculator;<br>circularity KPI mapping        | —      | —   | ✓     |
| Honeybee /<br>Ladybug                                                            | Operational energy &<br>daylight; Rhino/GH plugin          | ✓      | ~   | —     |
| <b>This Research:<br/>Excel Framework</b>                                        | Steady-state heat balance +<br>EPiC hybrid LCA + MCI       | ✓      | ✓   | ✓     |

✓ Covers ~ Partial — Not covered Circ. = Material Circularity (MCI) | GHG = Embodied GHG (LCA)

# The Research Opportunity

Three unresolved gaps define the need for an integrated framework

## Gap 1

### Metric

No tool links NatHERS energy performance to embodied GHG or MCI in a single compliance pathway.

## Gap 2

### Typology

Multi-residential pre-1980 buildings are absent from the retrofit research literature and all major software tools.

## Gap 3

### Methodology

Circular LCA accounting (incl. Module D and biogenic carbon) is not supported by a single retrofit-specific workflow.

# Scoping Decisions

Four deliberate choices that bound the investigation

## 01 Envelope Only

*Why not services or structure?*

Envelope upgrades (insulation, glazing, sealing) contribute 60–70% of thermal performance improvement. Services involve separate regulatory frameworks. Scope boundary keeps the framework tractable and replicable.

## 03 Australian Context

*Why not adapt an international tool?*

NatHERS is a closed-architecture 'black box': it cannot be parametrically linked to LCA. No existing Australian tool integrates energy, embodied GHG and circularity simultaneously.

## 02 1970s Multi-Residential

*Why this building typology?*

Pre-1980 multi-residential stock represents Australia's worst-performing cohort. It predates any thermal regulation and accounts for the largest unrealised efficiency gain. Often overlooked in policy — research dominated by detached housing.

## 04 Marginal Delta Approach

*Why not a whole-of-life LCA?*

Existing building materials are a sunk cost — GHG already emitted, cannot be recovered. Only the incremental embodied GHG of new retrofit materials is assessed. This is the most defensible accounting position (Vilches et al., 2017).

## SECTION 3: THE PROPOSED FRAMEWORK

# Research Aim

*To develop an integrated framework that evaluates energy retrofit strategies in residential buildings across three indicators simultaneously — without collapsing them into a single score — making trade-offs between strategies and material practices visible and usable for decision-making.*

### Energy Performance (B6)

**kWh/m<sup>2</sup>a**

Annual space heat demand via energy balance calculation (ISO 52016)

### Embodied Lifecycle GHG (A1-A3)

**kgCO<sub>2</sub>e**

Material GHG using EPiC hybrid coefficients · ISO 21930 / EN 15978

### Material Circularity (Information from Stage D – into A1-A3)

**MCI 0–1**

Virgin feedstock & recoverability potential via Ellen MacArthur Foundation formula

# Framework Architecture

The Brain and the Body: two inseparable but distinct contributions

## THE BRAIN — Theoretical Framework

A set of transferable principles and decision logic for assessing retrofit performance across three pillars. It specifies what to measure, how to account for uncertainty, and how to set performance thresholds.

- P1** Marginal delta system boundary — existing embodied GHG is sunk cost
- P2** Three-pillar integration — energy, embodied GHG, and circularity
- P3** Glass-box transparency — all calculations auditable and replicable
- P4** Performance benchmarking — threshold-based, not relative improvement
- P5** Typology specificity — calibrated for 1970s AU multi-residential

## THE BODY — Excel Instrument

A Microsoft Excel prototype that operationalises the framework. It enables parametric exploration of 54 retrofit scenarios across 9 strategies and 3 material variants.

- Input: building geometry, material assemblies, climate data
- Engine 1: quasi-steady-state heat balance (EN ISO 13790)
- Engine 2: hybrid LCA using EPiC database (A1–C4 + Module D)
- Engine 3: product-level MCI (Ellen MacArthur Foundation, 2019)
- Output: performance matrix + trade-off visualisation

**Key distinction:** The framework is the intellectual contribution. The instrument is the proof of concept. A different tool could implement the same framework.

## SECTION 3: THE PROPOSED FRAMEWORK

# Research Methodology — Three-Phase Framework

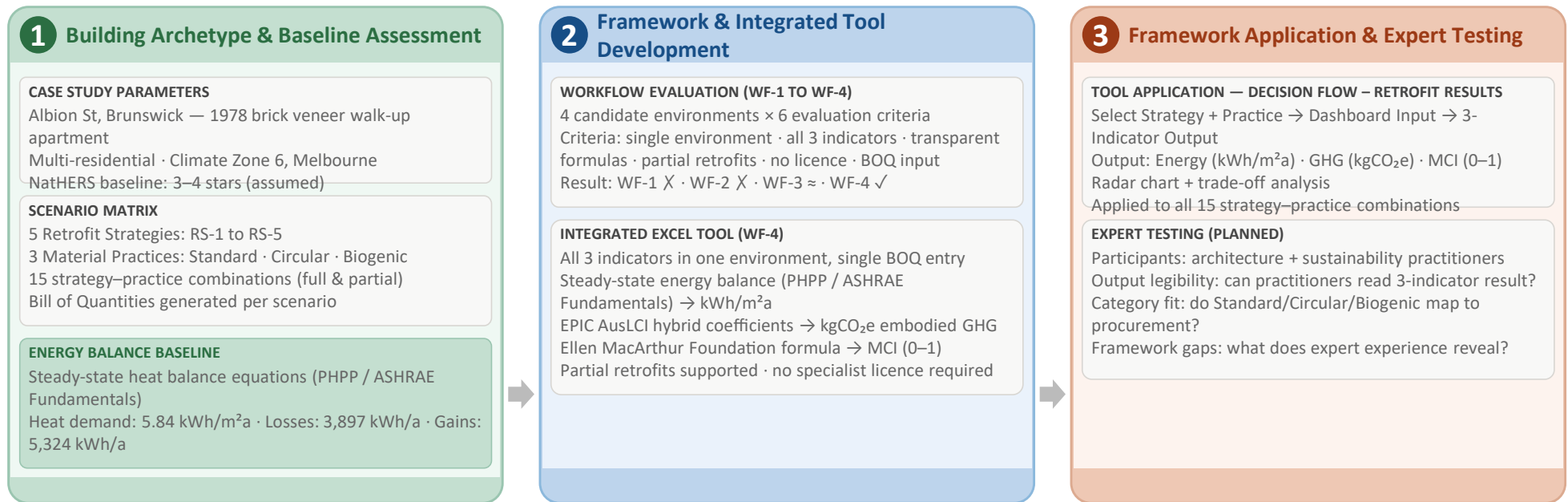


Figure 2. Three-phase research methodology for the development and application of the integrated retrofit evaluation framework.

# The Most Critical Design Decision

Why conventional LCA in RETROFIT PRACTICE over-counts embodied GHG — and what to do instead

## CONVENTIONAL APPROACH

*Whole-building LCA in Retrofit from scratch*

- ✗ Count ALL embodied GHG in the existing building
- ✗ Add new retrofit materials
- ✗ Compare total to an unretrofitted baseline

**Problem:** The existing building's embodied GHG was emitted decades ago and cannot be changed. Counting it inflates the apparent impact of the retrofit decision.

## MARGINAL DELTA APPROACH

*Vilches et al. (2017), adapted for Australian context*

- ✓ Existing building embodied GHG = sunk cost (assigned 0 kgCO<sub>2</sub>e)
- ✓ Only NEW retrofit materials are assessed (A1–A3)
- ✓ Compare incremental embodied GHG against incremental energy benefit

**Result:** A defensible, decision-relevant GHG account that measures only what can actually be changed by the retrofit decision.

**System boundary:** EC\_existing = 0 kgCO<sub>2</sub>e (sunk cost) EC\_retrofit = A1+A2+A3 of new materials only  
Reference: Vilches et al. (2017) Figure 2.1

## SECTION 3: THE PROPOSED FRAMEWORK

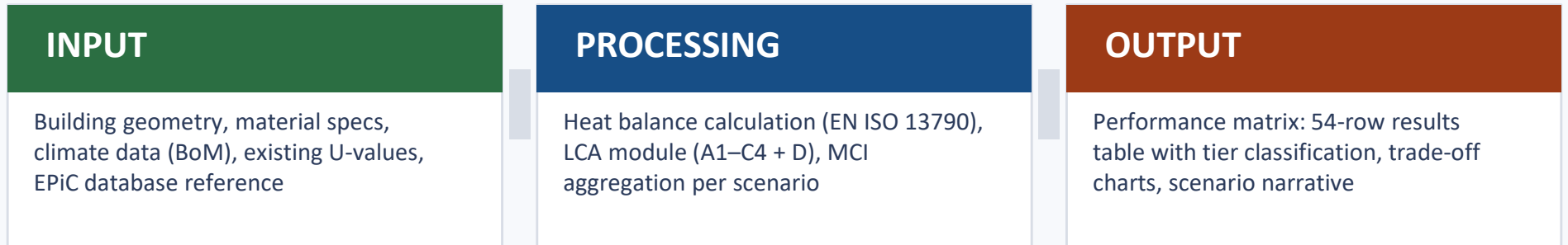
# Framework steps

Eight steps from baseline characterisation to performance synthesis (Figure 3.1)

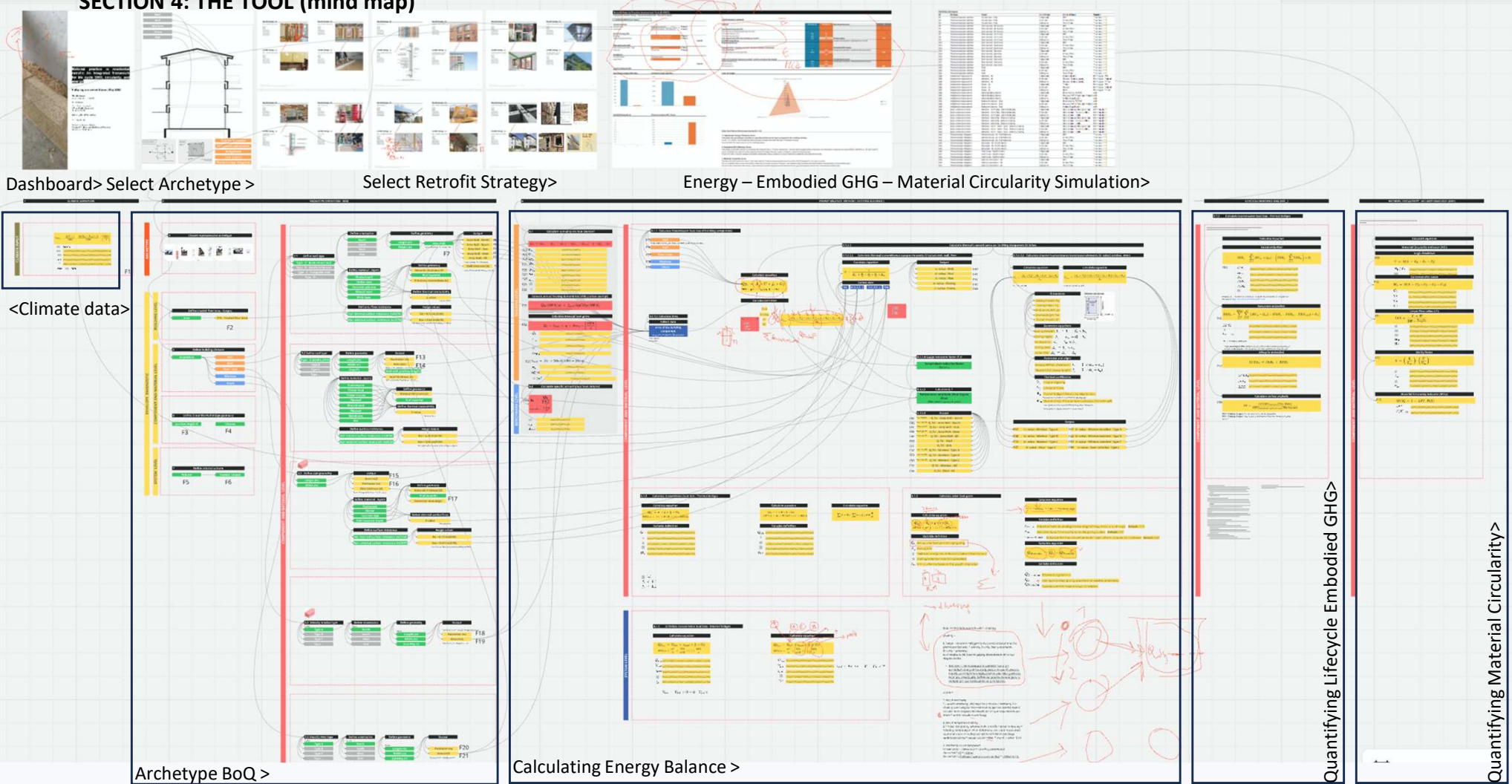
|          |                                                                                                                                                     |          |                                                                                                                              |
|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------|----------|------------------------------------------------------------------------------------------------------------------------------|
| <b>1</b> | <b>Define Scope &amp; Boundary</b><br>Typology, climate zone, envelope elements, marginal delta accounting rule                                     | <b>2</b> | <b>Characterise Baseline Archetype</b><br>Geometry, existing U-values, energy balance calculations, MCI baseline = 0.10      |
| <b>3</b> | <b>Identify Retrofit Strategies</b><br>9 envelope strategies across insulation, glazing, air-sealing, and combined package                          | <b>4</b> | <b>Develop Material Variants</b><br>Standard / Circular / Biogenic for each strategy — 27 material × strategy combinations   |
| <b>5</b> | <b>Calculate Operational Energy</b><br>Quasi-steady-state heat balance: $\Delta U \rightarrow \Delta Q \rightarrow$ NatHERS star rating equivalent* | <b>6</b> | <b>Calculate Embodied GHG</b><br>Hybrid LCA: EPiC A1–A3 (mandatory))                                                         |
| <b>7</b> | <b>Compute MCI Scores</b><br>Product-level MCI per material, aggregated by strategy scenario                                                        | <b>8</b> | <b>Synthesise Performance Matrix</b><br>54-scenario output: tier classification, trade-off analysis, scenario visualizations |

# Operational Workflow

How a user navigates the Excel instrument (Figure 3.2)



## SECTION 4: THE TOOL (mind map)



## SECTION 3: THE PROPOSED FRAMEWORK

# Workflow Evaluation — Criteria-Based Comparative Analysis

Six criteria derived from the research aim · WF-1 to WF-3: structured desktop review · WF-4: fully implemented

|                                                                     | Single environment | All 3 indicators | Transparent formulas | Partial retrofits | No specialist licence | BOQ single input |
|---------------------------------------------------------------------|--------------------|------------------|----------------------|-------------------|-----------------------|------------------|
| <b>WF-1</b><br>Dedicated Software<br>SimaPro · AccuRate · MCI calc  | X                  | ✓                | X                    | ~                 | X                     | X                |
| <b>WF-2</b><br>Rhino + Grasshopper<br>RhinoCircular · EPIC · IES VE | X                  | ✓                | ✓                    | ~                 | ~                     | ~                |
| <b>WF-3</b><br>PHPP + EPIC + MCI calc<br>Separate environments      | X                  | ✓                | ✓                    | ~                 | ~                     | ✓                |
| <b>WF-4 ★</b><br>Integrated Excel Tool<br>Selected approach         | ✓                  | ✓                | ✓                    | ✓                 | ✓                     | ✓                |

✓ Pass · X Fail · ~ Partial / possible but not a designed feature of those tools  
 Integrated Retrofit Framework — Claudio Torres | University of Melbourne — c.torressalazar@unimelb.edu.au

# Glass Box vs Black Box

Why first-principles modelling enables triple-pillar integration

NatHERS (AccuRate / FirstRate5)

## BLACK BOX

- ✗ Closed-source hourly simulation (AccuRate proprietary)
- ✗ Star rating output only — no accessible intermediate values
- ✗ Cannot be parametrically linked to LCA or MCI calculations
- ✗ No circular economy or embodied GHG module

This Research (Excel Instrument)

## GLASS BOX

- ✓ Quasi-steady-state method (EN ISO 13790 / PHPP-aligned)
- ✓ Every intermediate value visible and auditable in Excel
- ✓ U-values → heating loads → kWh/m<sup>2</sup>·a → kgCO<sub>2</sub>e → MCI in one chain
- ✓ Open-source EPiC database (Crawford, Stephan and Prideaux, 2024) for embodied C
- ✓ Fully parametric: change one input, all outputs update instantly

**Parametric chain:** U-value → ΔQ (kWh/m<sup>2</sup>·a) → ΔCO<sub>2</sub>e (kgCO<sub>2</sub>e/m<sup>2</sup>) → ΔMCI — all computable simultaneously in one instrument

# What the Instrument Produces

One BoQ input. 60 scenarios. Three indicators. No single score.

## Performance Matrix

60-row results table with scores for each indicator. Scenarios classified into High / Performing / Low tiers. Exportable for further analysis.

## Trade-off Visualisation

Scatter plot: Embodied GHG (x) vs MCI (y), with NatHERS star rating encoded as point size. Identifies optimal scenarios and dominant trade-offs.

## Scenario Narrative

Automated interpretation: Which strategy combination achieves the best balanced performance? What are the environmental costs for high-circularity vs high-energy choices?

## Sensitivity Dashboard

How sensitive is each output to material variant choice? Biogenic vs Circular vs Standard — marginal delta for each pillar.

## SECTION 4: THE SOFTWARE TOOL

# Case Study: Albion Street, Brunswick

The baseline archetype — selected for typological representativeness and data availability

|                   |                                                                |
|-------------------|----------------------------------------------------------------|
| Construction year | 1978 (pre-thermal regulation)                                  |
| Location          | Brunswick, VIC (Climate Zone 6)                                |
| Typology          | Multi-residential apartment — 2 floors, 10 units (5 per floor) |
| Structure         | Brick veneer; concrete slabs; single-pane aluminium windows    |
| Baseline NatHERS  | - To be determined                                             |
| Baseline MCI      | -                                                              |
| Target            | -                                                              |

### Why this building?

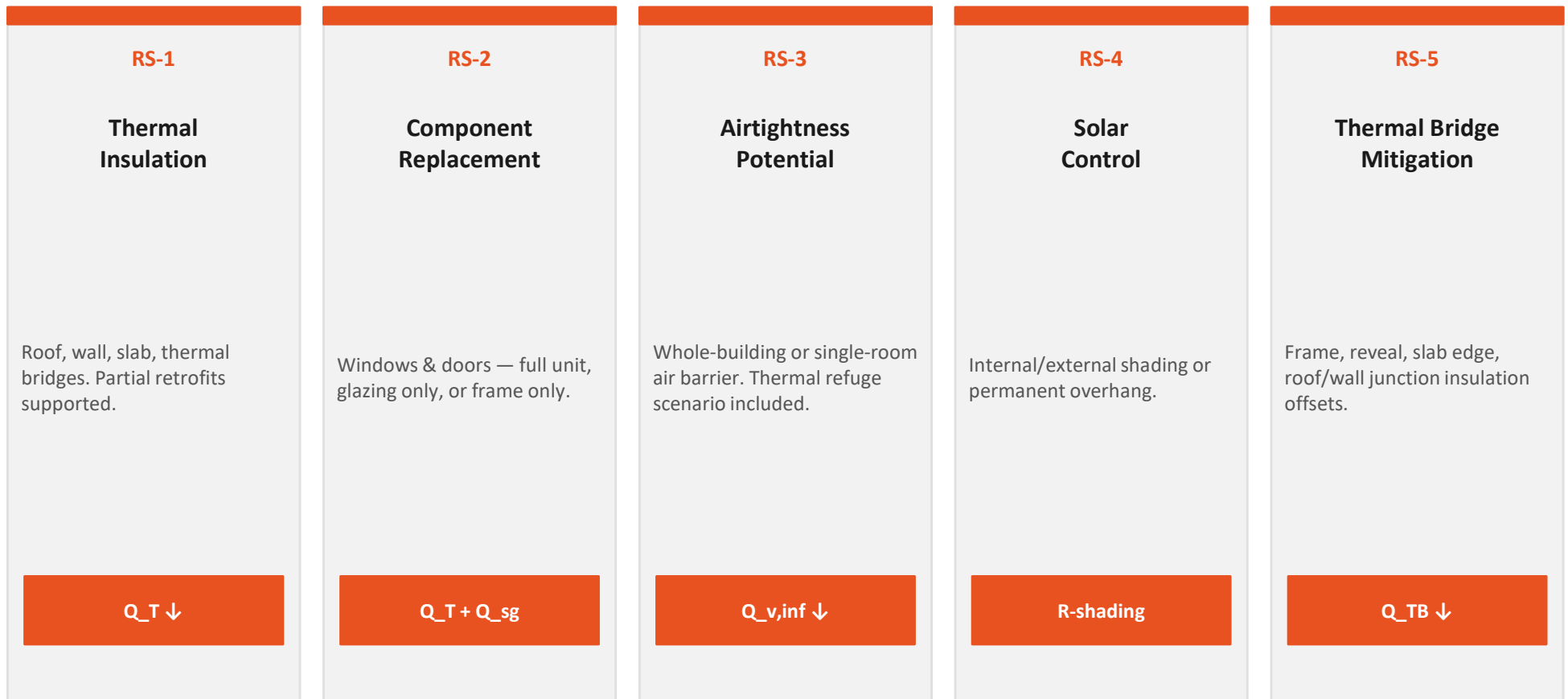
Represents the dominant pre-1980 Victorian walk-up apartment typology. Documentation available. Baseline energy performance assessed via energy balance equations. Tenure mix (strata) reflects policy complexity.



267 ALBION STREET  
BRUNSWICK



# Retrofit Strategies Variations



## SECTION 4: THE SOFTWARE TOOL

# Material Practices Variations

Each retrofit strategy is assessed across three distinct environmental profiles — hold the strategy constant, vary only the material.

### A — Standard Practice

#### Example:

*EPS insulation board, standard uPVC window frames*

Widely used because they are cheap, easy to install, and energy-efficient. Industry default. High environmental impact; poor end-of-life recoverability.



Benchmark

### B — Circular Practice

#### Example:

*Reused timber profiles, vacuum glazing from decommissioned buildings*

Recovered from previous use cycles. Declared virgin feedstock and recoverability values. Environmental signature measurable through the MCI formula.



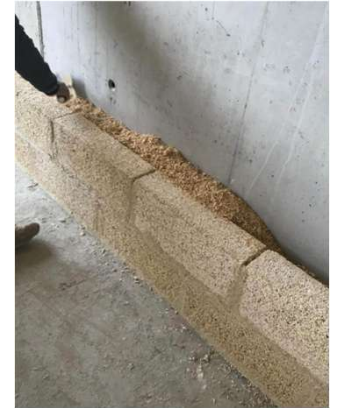
Measured via MCI

### C — Biogenic Practice

#### Example:

*Wood fibre board insulation, timber window frames*

Renewable biological sources. Declared virgin feedstock ratio and end-of-life recoverability. Can partially offset embodied GHG through carbon sequestration.



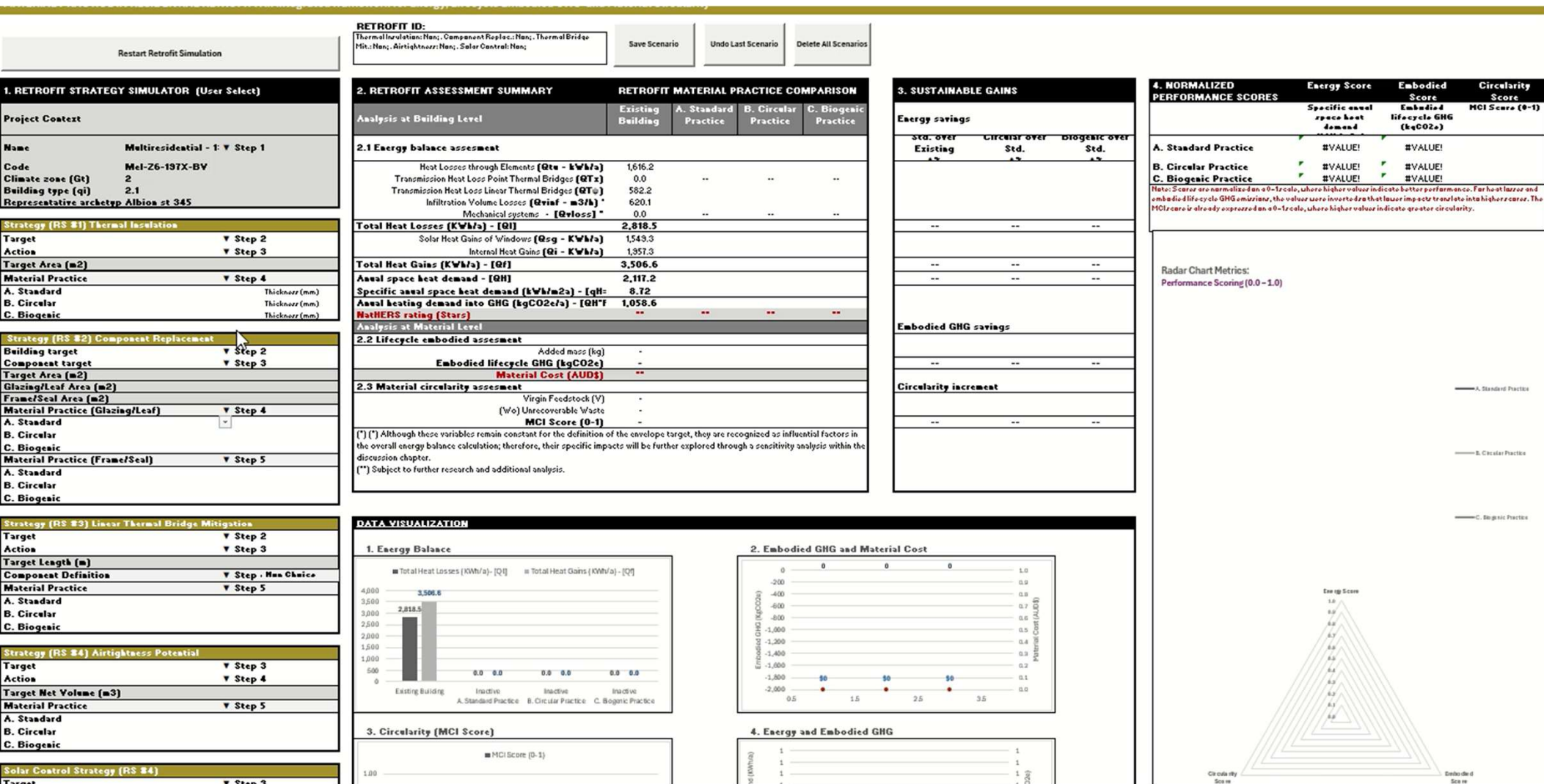
Carbon sequestration

## SECTION 4: THE SOFTWARE TOOL

# The 60-Scenario Retrofit Matrix

5 retrofit strategies · 20 actions across 13 envelope targets · 3 material practices

| Retrofit Strategy                                                                                                                   | Standard (A)                                                                          | Circular (B)                                                                          | Biogenic (C)                                                                          |
|-------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| <b>Thermal Insulation</b><br><i>Walls (external · internal) — Roof (external · internal) — Slab (internal)</i>                      |    |    |    |
| <b>Component Replacement</b><br><i>Windows: glaz+frame · glazing only · frame only — Doors: leaf+frame · leaf only · frame only</i> |    |    |    |
| <b>Airtightness Potential</b><br><i>Volume: primary air barrier — Bedroom: thermal refuge</i>                                       |    |    |    |
| <b>Solar Control</b><br><i>Windows: permanent external overhang — temporary external shading</i>                                    |   |   |   |
| <b>Linear Thermal Bridge Mitigation</b><br><i>Window edges · Door edges · Slab edge · Roof / wall junction</i>                      |  |  |  |
| <b>Total:</b> 5 strategies · 20 actions × 3 material practices = <b>60 scenarios</b>                                                |                                                                                       |                                                                                       |                                                                                       |



# Dashboard Output

Retrofit Strategy Assessment Tool — live output (RS-1 Thermal Insulation, Standard Practice)

|                          |                |
|--------------------------|----------------|
| Code                     | Mel-26-197X-BV |
| Climate zone (G1)        | 2              |
| Building type (G1)       | 2.1            |
| Representative archetype | Albion at 345  |

|                                     |                     |                   |
|-------------------------------------|---------------------|-------------------|
| Strategy (RS #1) Thermal Insulation |                     |                   |
| Target                              | Walls, All          | ▼ Step 2          |
| Action                              | External Insulation | ▼ Step 3          |
| Target Area (m <sup>2</sup> )       | 283.16              |                   |
| Material Practice                   |                     |                   |
| ▼ Step 4                            |                     |                   |
| A. Standard                         | EPS Board           | 50 Thickness (mm) |
| B. Circular                         | Recycled Polyester  | 50 Thickness (mm) |
| C. Biogenic                         | Wood Fiber Board    | 50 Thickness (mm) |

|                                        |                   |          |
|----------------------------------------|-------------------|----------|
| Strategy (RS #2) Component Replacement |                   |          |
| Building target                        | Windows, All      | ▼ Step 2 |
| Component target                       | Glazing And Frame | ▼ Step 3 |
| Target Area (m <sup>2</sup> )          | Glazing And Frame |          |
| Glazing/Leaf Area (m <sup>2</sup> )    | Glazing           |          |
| Frame/Seal Area (m <sup>2</sup> )      | Glazing           |          |
| Material Practice                      |                   |          |
| ▼ Step 5                               |                   |          |
| A. Standard                            |                   |          |
| B. Circular                            |                   |          |
| C. Biogenic                            |                   |          |
| Material Practice (Frame/Seal)         |                   |          |
| ▼ Step 5                               |                   |          |
| A. Standard                            |                   |          |
| B. Circular                            |                   |          |
| C. Biogenic                            |                   |          |

|                                                   |  |                      |
|---------------------------------------------------|--|----------------------|
| Strategy (RS #3) Linear Thermal Bridge Mitigation |  |                      |
| Target                                            |  | ▼ Step 2             |
| Action                                            |  | ▼ Step 3             |
| Target Length (m)                                 |  |                      |
| Component Definition                              |  | ▼ Step 4: New Choice |
| Material Practice                                 |  |                      |
| ▼ Step 5                                          |  |                      |
| A. Standard                                       |  |                      |
| B. Circular                                       |  |                      |
| C. Biogenic                                       |  |                      |

|                                         |  |          |
|-----------------------------------------|--|----------|
| Strategy (RS #4) Airtightness Potential |  |          |
| Target                                  |  | ▼ Step 3 |
| Action                                  |  | ▼ Step 4 |
| Target Net Volume (m <sup>3</sup> )     |  |          |
| Material Practice                       |  |          |
| ▼ Step 5                                |  |          |
| A. Standard                             |  |          |
| B. Circular                             |  |          |
| C. Biogenic                             |  |          |

|                                       |  |          |
|---------------------------------------|--|----------|
| Solar Control Strategy (RS #5)        |  |          |
| Target                                |  | ▼ Step 3 |
| Action                                |  | ▼ Step 4 |
| Glass Definition                      |  | ▼ Step 5 |
| Target Glazing Area (m <sup>2</sup> ) |  |          |
| Material Practice                     |  |          |
| ▼ Step 5                              |  |          |
| A. Standard Practice                  |  |          |
| B. Circular Practice                  |  |          |
| C. Biogenic Practice                  |  |          |

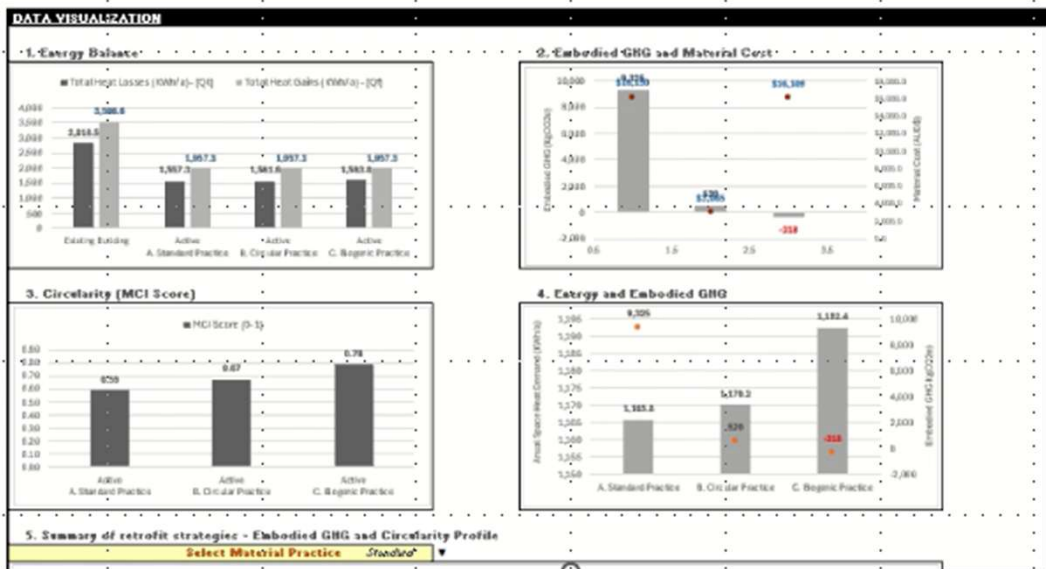
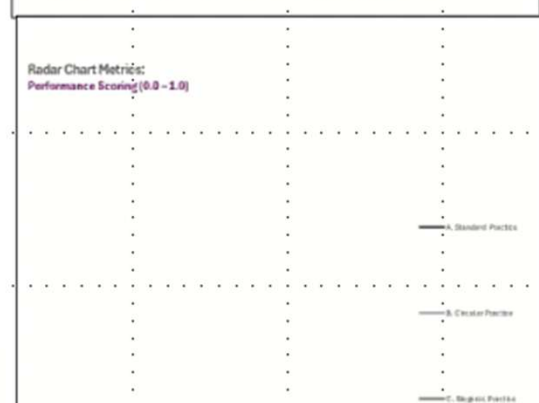
|                                                                              |         |          |         |          |
|------------------------------------------------------------------------------|---------|----------|---------|----------|
| Heat Losses through Elements (Q <sub>loss</sub> - kW/h)                      | 1,516.2 | 1,557.3  | 1,561.6 | 1,583.8  |
| Transmission Heat Loss Point Thermal Bridges (Q <sub>tr</sub> )              | 0.0     | ...      | ...     | ...      |
| Transmission Heat Loss Linear Thermal Bridges (Q <sub>lt</sub> )             | 582.2   | ...      | ...     | ...      |
| Infiltration Volume Losses (Q <sub>infil</sub> - m <sup>3</sup> /h)          | 600.4   | ...      | ...     | ...      |
| Mechanical systems - (Q <sub>mech</sub> ) *                                  | 0.0     | ...      | ...     | ...      |
| Total Heat Losses (kW/h) - (Q <sub>l</sub> )                                 | 2,818.5 | 1,557.3  | 1,561.6 | 1,583.8  |
| Solar Heat Gains of Windows (Q <sub>sg</sub> - kW/h)                         | 1,543.3 | ...      | ...     | ...      |
| Internal Heat Gains (Q <sub>i</sub> - kW/h)                                  | 1,357.3 | 1,357.3  | 1,357.3 | 1,357.3  |
| Total Heat Gains (kW/h) - (Q <sub>g</sub> )                                  | 3,506.6 | 1,357.3  | 1,357.3 | 1,357.3  |
| Annual space heat demand - (Q <sub>H</sub> )                                 | 2,117.2 | 1,165.8  | 1,176.2 | 1,192.4  |
| Specific annual space heat demand (kWh/m <sup>2</sup> a) - (q <sub>H</sub> ) | 8.72    | 4.80     | 4.82    | 4.31     |
| Annual heating demand into GHG (kgCO <sub>2</sub> e/a) - (Q <sub>H</sub> *)  | 1,058.6 | 582.3    | 585.1   | 556.2    |
| MATERIALS rating (Stars)                                                     |         |          |         |          |
| Analysis at Material Level                                                   |         |          |         |          |
| 2.2 Lifecycle embodied assessment                                            |         |          |         |          |
| Added mass (kg)                                                              | ...     | 144.6    | 144.6   | 144.6    |
| Embodied lifecycle GHG (kgCO <sub>2</sub> e)                                 | ...     | 3,325.4  | 520.5   | -318.1   |
| Material Cost (AUD)                                                          | ...     | 16,149.6 | 5,065.1 | 16,103.1 |
| 2.3 Material circularity assessment                                          |         |          |         |          |
| Virgin Feedstock (V)                                                         | ...     | 68.7     | 50.8    | 3.6      |
| (V%) Unrecoverable Waste                                                     | ...     | 72.3     | -7.2    | 0.0      |
| MCI Score (0-1)                                                              | ...     | 0.53     | 0.67    | 0.78     |

(\*) Although these variables remain constant for the definition of the envelope target, they are recognized as influential factors in the overall energy balance calculation; therefore, their specific impacts will be further explored through a sensitivity analysis within the discussion chapter.  
(\*\*) Subject to further research and additional analysis.

|                       |        |         |
|-----------------------|--------|---------|
| -44.7%                | 0.3%   | 1.7%    |
| -44.2%                | 0.0%   | 0.0%    |
| -44.3%                | 0.4%   | 2.3%    |
| Embodied GHG savings  |        |         |
| ...                   | -94.4% | -103.4% |
| Circularity increment |        |         |
| ...                   | 13.7%  | 35.4%   |

|                      |     |     |     |
|----------------------|-----|-----|-----|
| B. Circular Practice | 0.8 | 0.9 | 0.7 |
| C. Biogenic Practice | 0.0 | 1.0 | 0.6 |

Note: Scores are normalized on a 0-1 scale, where higher values indicate better performance. For heat losses and embodied lifecycle GHG savings, the higher value represents a greater negative impact (higher saving). The MCI score is already a percentage on the scale, where higher values indicate greater circularity.



WORK IN PROGRESS

# Dashboard Output

Retrofit Strategy Assessment Tool — live output (RS-1 Thermal Insulation, Standard Practice)

|                          |                |
|--------------------------|----------------|
| Code                     | Mel-26-157X-BV |
| Climate zone (Cl)        | 2              |
| Building type (qt)       | 2.1            |
| Representative archetype | Albion at 345  |

|                                     |                     |                   |
|-------------------------------------|---------------------|-------------------|
| Strategy (RS #1) Thermal Insulation |                     |                   |
| Target                              | Walls_All           | Step 2            |
| Action                              | External_Insulation | Step 3            |
| Target Area (m <sup>2</sup> )       | 289.16              |                   |
| Material Practice                   |                     |                   |
| Step 4                              |                     |                   |
| A. Standard                         | EPS Board           | 50 Thickness (mm) |
| B. Circular                         | Recycled Polyester  | 50 Thickness (mm) |
| C. Biogenic                         | Wood Fiber Board    | 50 Thickness (mm) |

|                                        |               |        |
|----------------------------------------|---------------|--------|
| Strategy (RS #2) Component Replacement |               |        |
| Building target                        | Windows_All   | Step 2 |
| Component target                       | Windows_North | Step 3 |
| Target Area (m <sup>2</sup> )          | Windows_South |        |
| Glazing/Leaf Area (m <sup>2</sup> )    | Windows_East  |        |
| Frame/Seal Area (m <sup>2</sup> )      | Windows_West  |        |
| Material Practice (Glazing)            |               |        |
| Step 4                                 |               |        |
| A. Standard                            | Doors_All     |        |
| B. Circular                            | Doors_North   |        |
| C. Biogenic                            | Doors_South   |        |
| Material Practice (Frame)              |               |        |
| Step 5                                 |               |        |
| A. Standard                            | Doors_East    |        |
| B. Circular                            | Doors_West    |        |
| C. Biogenic                            |               |        |

|                         |             |        |
|-------------------------|-------------|--------|
| Strategy (RS #3) Linear |             |        |
| Target                  | Doors_North | Step 2 |
| Action                  | Doors_South | Step 3 |
| Target Length (m)       | Doors_East  |        |
| Component Definition    | Doors_West  |        |
| Material Practice       |             |        |
| Step 5                  |             |        |
| A. Standard             |             |        |
| B. Circular             |             |        |
| C. Biogenic             |             |        |

|                                         |  |        |
|-----------------------------------------|--|--------|
| Strategy (RS #4) Airtightness Potential |  |        |
| Target                                  |  | Step 3 |
| Action                                  |  | Step 4 |
| Target Net Volume (m <sup>3</sup> )     |  |        |
| Material Practice                       |  |        |
| Step 5                                  |  |        |
| A. Standard                             |  |        |
| B. Circular                             |  |        |
| C. Biogenic                             |  |        |

|                                       |  |        |
|---------------------------------------|--|--------|
| Solar Control Strategy (RS #4)        |  |        |
| Target                                |  | Step 3 |
| Action                                |  | Step 4 |
| Glass Definition                      |  | Step 5 |
| Target Glazing Area (m <sup>2</sup> ) |  |        |
| Material Practice                     |  |        |
| Step 5                                |  |        |
| A. Standard Practice                  |  |        |
| B. Circular Practice                  |  |        |
| C. Biogenic Practice                  |  |        |

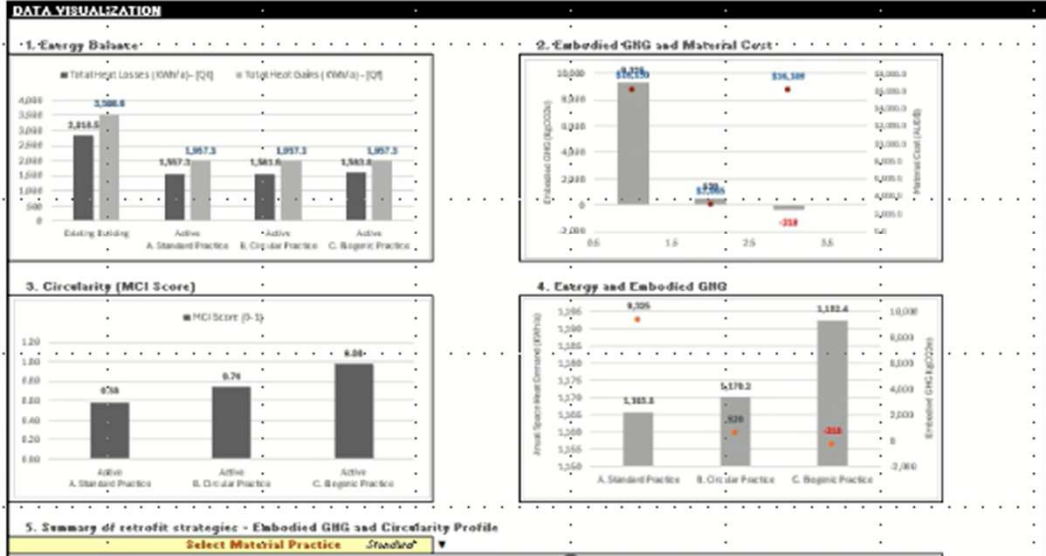
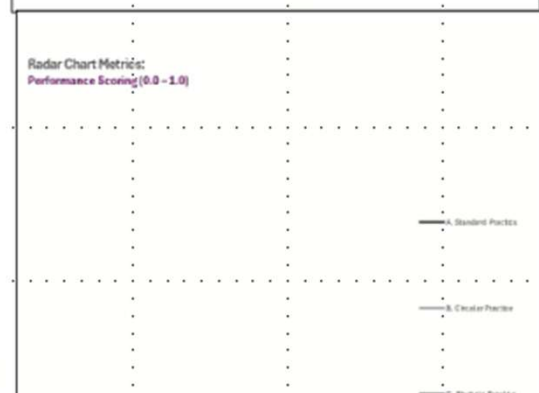
|                                                                              |         |          |         |          |
|------------------------------------------------------------------------------|---------|----------|---------|----------|
| Heat Losses through Elements (Q <sub>loss</sub> - kW/h)                      | 1,516.2 | 1,557.3  | 1,561.6 | 1,583.8  |
| Transmission Heat Loss Point Thermal Bridges (Q <sub>tx</sub> )              | 0.0     | ...      | ...     | ...      |
| Transmission Heat Loss Linear Thermal Bridges (Q <sub>tl</sub> )             | 582.2   | ...      | ...     | ...      |
| Infiltration Volume Losses (Q <sub>vol</sub> - m <sup>3</sup> /h)            | 600.4   | ...      | ...     | ...      |
| Mechanical systems - (Q <sub>mech</sub> )                                    | 0.0     | ...      | ...     | ...      |
| Total Heat Losses (kW/h) - (Q <sub>l</sub> )                                 | 2,818.5 | 1,557.3  | 1,561.6 | 1,583.8  |
| Solar Heat Gains of Windows (Q <sub>sg</sub> - kW/h)                         | 1,543.3 | ...      | ...     | ...      |
| Internal Heat Gains (Q <sub>i</sub> - kW/h)                                  | 1,357.3 | 1,357.3  | 1,357.3 | 1,357.3  |
| Total Heat Gains (kW/h) - (Q <sub>g</sub> )                                  | 3,506.6 | 1,357.3  | 1,357.3 | 1,357.3  |
| Annual space heat demand (Q <sub>H</sub> )                                   | 2,117.2 | 1,165.8  | 1,176.2 | 1,192.4  |
| Specific annual space heat demand (kWh/m <sup>2</sup> a) - (q <sub>H</sub> ) | 8.72    | 4.80     | 4.82    | 4.31     |
| Annual heating demand into GHG (kgCO <sub>2</sub> e/a) - (Q <sub>H</sub> *)  | 1,058.6 | 582.3    | 585.1   | 556.2    |
| Materials rating (Stars)                                                     | ...     | ...      | ...     | ...      |
| Analysis at Material Level                                                   |         |          |         |          |
| 2.2 Lifecycle embodied assessment                                            |         |          |         |          |
| Added mass (kg)                                                              | ...     | 144.6    | 144.6   | 144.6    |
| Embodied lifecycle GHG (kgCO <sub>2</sub> e)                                 | ...     | 3,325.4  | 520.5   | -318.1   |
| Material Cost (AUD\$)                                                        | ...     | 16,149.6 | 5,065.1 | 16,109.1 |
| 2.3 Material circularity assessment                                          |         |          |         |          |
| Virgin Feedstock (V)                                                         | ...     | 137.4    | 912     | 7.2      |
| (V%) Unrecoverable Waste                                                     | ...     | 144.6    | -143    | 0.0      |
| MCI Score (0-1)                                                              | ...     | 0.58     | 0.74    | 0.98     |

(\*) Although these variables remain constant for the definition of the envelope target, they are recognized as individual factors in the overall energy balance calculation; therefore, their specific impacts will be further explored through a sensitivity analysis within the discussion chapters.  
(\*\*) Subject to further research and additional analysis.

|                                              |        |         |      |
|----------------------------------------------|--------|---------|------|
| Total Heat Losses (kW/h) - (Q <sub>l</sub> ) | -44.7% | 0.3%    | 1.7% |
| Total Heat Gains (kW/h) - (Q <sub>g</sub> )  | -44.2% | 0.0%    | 0.0% |
| Annual space heat demand (Q <sub>H</sub> )   | -44.3% | 6.4%    | 2.3% |
| Embodied GHG savings                         |        |         |      |
| ...                                          | ...    | ...     | ...  |
| ...                                          | -94.4% | -103.4% |      |
| Circularity increment                        |        |         |      |
| ...                                          | ...    | ...     | ...  |
| ...                                          | 27.6%  | 67.5%   |      |

|                      |     |     |     |
|----------------------|-----|-----|-----|
| B. Circular Practice | 0.8 | 0.9 | 0.7 |
| C. Biogenic Practice | 0.0 | 1.0 | 1.0 |

Note: Scores are normalized on a 0-1 scale, where higher values indicate better performance. For heat losses and embodied lifecycle GHG savings, the values under Biogenic (for the Biogenic Practice) are slightly higher than the others. The MCI scores are already a percentage, where higher values indicate greater circularity.



WORK IN PROGRESS

# Dashboard Output

Retrofit Strategy Assessment Tool — live output (RS-1 Thermal Insulation, Standard Practice)

Code: Mel-26-19TX-BV  
Climate zone (G): 2  
Building type (q): 2.1  
Representative archetype: Albion at 345

**Strategy (RS #1) Thermal Insulation**  
Target: Walls\_All ▼ Step 2  
Action: External\_Insulation ▼ Step 3  
Target Area (m<sup>2</sup>): 283.16  
Material Practice: ▼ Step 4  
A. Standard EPS Board 50 Thickness (mm)  
B. Circular Recycled Polyester 50 Thickness (mm)  
C. Biogenic Wood Fiber Board 50 Thickness (mm)

**Strategy (RS #2) Component Replacement**  
Building target: Windows\_All ▼ Step 2  
Component target: Glazing\_And\_Fram ▼ Step 3  
Target Area (m<sup>2</sup>): 28.38  
Glazing/Leaf Area (m<sup>2</sup>): 20.62  
Frame/Seal Area (m<sup>2</sup>): 7.8  
Material Practice (Glazing/Leaf): ▼ Step 4  
A. Standard Double Glazing  
B. Circular Vacuum Glazing  
C. Biogenic Low-E Glazing  
Material Practice (Frame/Seal): ▼ Step 5  
A. Standard uPVC Profile  
B. Circular  
C. Biogenic  
Exist. Alum.

**Strategy (RS #3) Linear Thermal Bridge Mitigation**  
Target: ▼ Step 2  
Action: ▼ Step 3  
Target Length (m):  
Component Definition: ▼ Step 4  
Material Practice: ▼ Step 5  
A. Standard  
B. Circular  
C. Biogenic

**Strategy (RS #4) Airtightness Potential**  
Target: ▼ Step 3  
Action: ▼ Step 4  
Target Net Volume (m<sup>3</sup>):  
Material Practice: ▼ Step 5  
A. Standard Practice  
B. Circular Practice  
C. Biogenic Practice

**Solar Control Strategy (RS #5)**  
Target: ▼ Step 3  
Action: ▼ Step 4  
Glaze Definition: ▼ Step 5  
Target Glazing Area (m<sup>2</sup>):  
Material Practice: ▼ Step 5  
A. Standard Practice  
B. Circular Practice  
C. Biogenic Practice

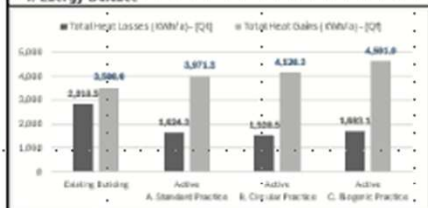
|                                                                             |                |                |                |                |
|-----------------------------------------------------------------------------|----------------|----------------|----------------|----------------|
| Heat Losses through Elements (Q <sub>te</sub> - kWh/a)                      | 1,516.2        | 1,624.3        | 1,528.5        | 1,663.1        |
| Transmission Heat Loss Point Thermal Bridges (Q <sub>tr</sub> )             | 0.0            | ...            | ...            | ...            |
| Transmission Heat Loss Linear Thermal Bridges (Q <sub>tl</sub> )            | 582.2          | ...            | ...            | ...            |
| Infiltration Volume Losses (Q <sub>vol</sub> - m <sup>3</sup> /h)           | 620.4          | ...            | ...            | ...            |
| Mechanical systems - (Q <sub>mech</sub> ) *                                 | 0.0            | ...            | ...            | ...            |
| <b>Total Heat Losses (Q<sub>th</sub>) - (Q<sub>te</sub>)</b>                | <b>2,818.5</b> | <b>1,624.3</b> | <b>1,528.5</b> | <b>1,663.1</b> |
| Solar Heat Gains of Windows (Q <sub>sg</sub> - kWh/a)                       | 1,543.3        | 2,014.0        | 2,169.0        | 2,633.0        |
| Internal Heat Gains (Q <sub>i</sub> - kWh/a)                                | 1,357.3        | 1,357.3        | 1,357.3        | 1,357.3        |
| <b>Total Heat Gains (Q<sub>th</sub>) - (Q<sub>sg</sub>)</b>                 | <b>3,506.6</b> | <b>3,371.3</b> | <b>4,126.3</b> | <b>4,531.0</b> |
| Annual space heat demand (Q <sub>h</sub> )                                  | 2,117.2        | 830.0          | 703.3          | 764.3          |
| Specific annual space heat demand (kWh/m <sup>2</sup> ) - (q <sub>h</sub> ) | 8.72           | 3.42           | 2.30           | 3.15           |
| Annual heating demand into GHG (kgCO <sub>2</sub> e) - (Q <sub>h</sub> )    | 1,058.6        | 415.0          | 351.6          | 382.5          |
| <b>Waters rating (Stars)</b>                                                | <b>**</b>      | <b>**</b>      | <b>**</b>      | <b>**</b>      |

|                                              |             |                 |                 |                 |
|----------------------------------------------|-------------|-----------------|-----------------|-----------------|
| <b>Analysis at Material Level</b>            |             |                 |                 |                 |
| <b>2.2 Lifecycle embodied assessment</b>     |             |                 |                 |                 |
| Added mass (kg)                              | 145.1       | 174.0           | 144.7           |                 |
| Embodied lifecycle GHG (kgCO <sub>2</sub> e) | 9,550.0     | 686.0           | -318.7          |                 |
| <b>Material Cost (AUD\$)</b>                 | <b>**</b>   | <b>20,724.6</b> | <b>23,562.0</b> | <b>10,685.6</b> |
| <b>2.3 Material circularity assessment</b>   |             |                 |                 |                 |
| Virgin Feedstock (V)                         | 63.4        | 62.8            | 3.6             |                 |
| (%) Unrecoverable Waste                      | 73.0        | -11             | 0.0             |                 |
| <b>MCI Score (0-1)</b>                       | <b>0.58</b> | <b>0.60</b>     | <b>0.54</b>     |                 |

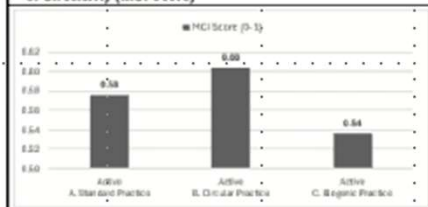
(\*) (\*) Although these variables remain constant for the design target, they are recognized as influential factors in the overall energy balance calculation; therefore, their specific impacts will be further explored through a sensitivity analysis within the discussion chapter.  
(\*\*) Subject to further research and additional analysis.

## DATA VISUALIZATION

### 1. Energy Balance



### 3. Circularity (MCI Score)



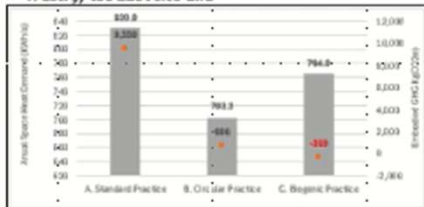
### 5. Summary of retrofit strategies - Embodied GHG and Circularity Profile

Select Material Practice: Standard ▼

### 2. Embodied GHG and Material Cost

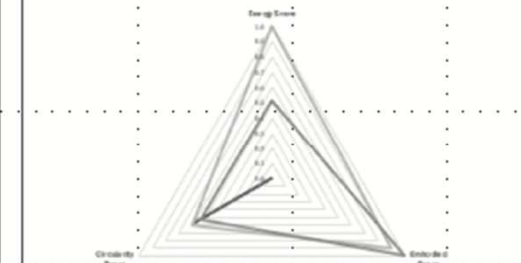


### 4. Energy and Embodied GHG



**B. Circular Practice** 1.0 0.9 0.6  
**C. Biogenic Practice** 0.5 10 0.5  
Note: Scores are normalized on a 0-10 scale, where higher values indicate better performance. For heat losses and embodied lifecycle GHG emissions, the ratings were inverted so that lower ratings represent higher values. The MCI score is already a percentage, where higher values indicate greater circularity.

Radar Chart Metrics:  
Performance Scoring (0.0 - 1.0)



WORK IN PROGRESS

## SECTION 5: NEXT STEPS

# Research Timeline & Pending Work

Current status and the path to thesis completion

### COMPLETED

Chapters 1–3 drafted — Scope, Literature Review, Research Design; baseline archetype characterised; Excel instrument prototype built; 54-scenario matrix defined

### IN PROGRESS

Running full 60-scenario simulation suite; refining energy, embodied GHG and MCI calculations for material variants; consolidating chapter 3, drafting Chapter 4 (Framework) and drafting Chapter 5 (Tool)

### NEXT 12 MONTHS

Expert review panel (Phase 1 validation); industry consultation sessions; Chapter 5 (Tool) drafting and external software validation (Phase 2 validation); Chapter 6 (Results) drafting; case study expansion to second building typology (if feasible)

### FINAL STAGE

Thesis submission (target S2-2028); planning a conference paper on preliminary results on the integration framework for Australian retrofits; tool documentation for open-source release

## ACKNOWLEDGEMENTS

### ACADEMIC SUPERVISION

#### **Prof. Robert Crawford**

Principal Supervisor — Life Cycle Assessment & Embodied GHG

#### **A/Prof. Djordje Stojanovic**

Co-Supervisor — Architecture & Retrofit Design

#### **Dr James Helal**

Co-Supervisor — Life Cycle Assessment & Software advice

#### **Prof. Sarah Bell**

Advisory — Infrastructure Sustainability

*Guidance and feedback throughout the thesis*

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#### **Daniel Kress**

Industry Expert — Passive House / PHPP

*Guidance on the tool's ASHRAE/ISO thermodynamic basis.*

### ENERGY MODELLING & NatHERS

#### **Jorge Riesco**

Environmental Designer, Finding Infinity

NatHERS Certifier

*Feedback on NatHERS translation  
methodology and energy modelling setup*

### TOOL DEVELOPMENT

#### **Sebastián Ilabaca**

Software Engineer & Data Analyst

*Provided assistance in developing the integrated evaluation tool.*

### CASE STUDY ACCESS

#### **Stephen Thick**

Architect

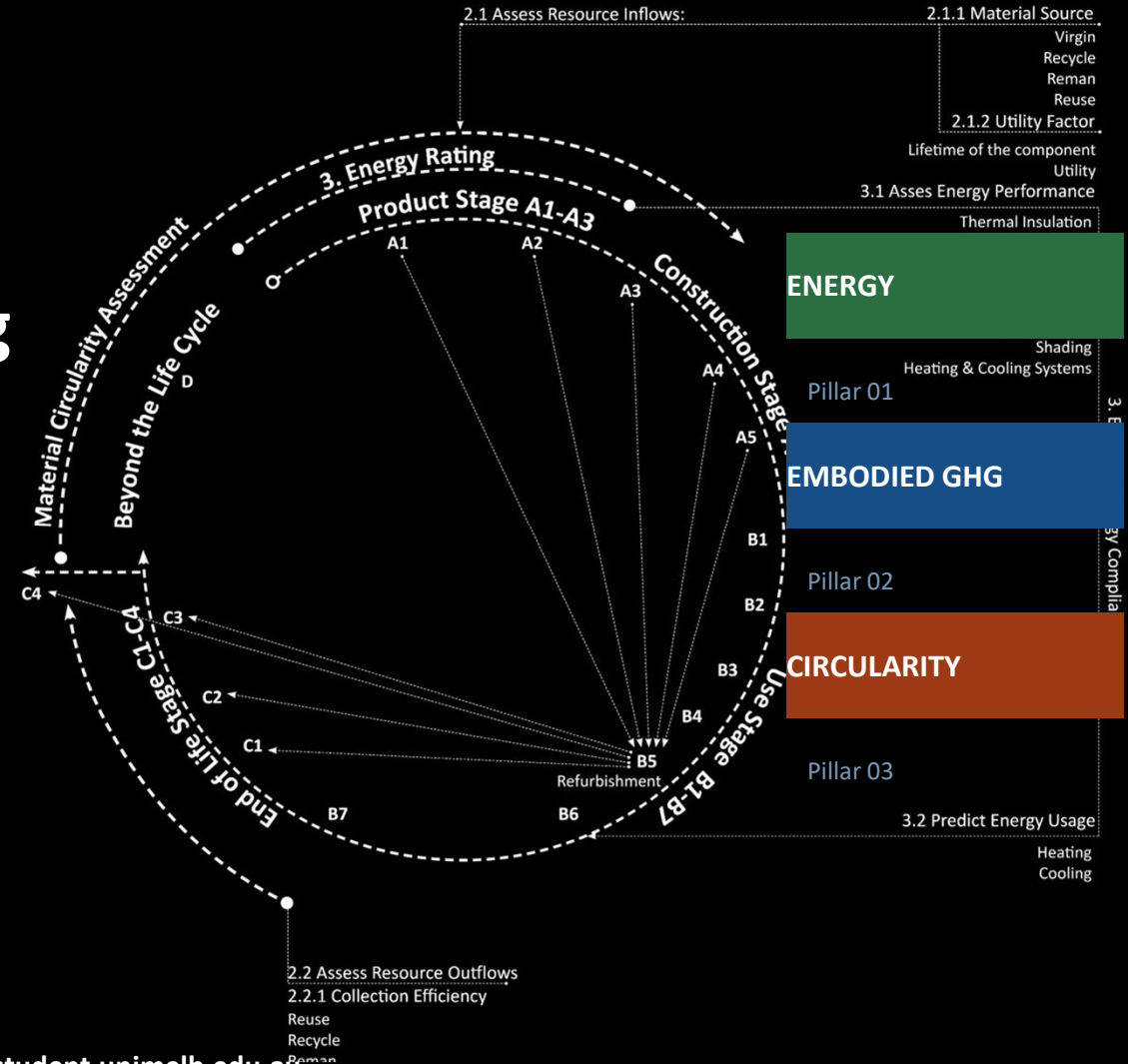
*Facilitated access to information on the brick veneer building  
typology studied in this project*

# An integrated, glass-box assessment framework for retrofit decision-making

A defensible GHG accounting position that measures only the retrofit decision — not sunk costs.

First framework to simultaneously assess operational energy, embodied GHG and circularity for AU multi-residential retrofits.

A transparent, auditable, parametric Excel tool enabling 60-scenario exploration without closed-source software.



Comments, feedback, and questions welcome → [c.torressalazar@student.unimelb.edu.au](mailto:c.torressalazar@student.unimelb.edu.au)