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# Digital Technologies for Sustainability-Oriented Decision-Making: Integrating BIM and Computational Programming for Building Envelope Selection

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**Abstract**

The growing environmental impact of the construction sector is driving a shift toward sustainable design practices, in which digital technologies are integrated to enable designers to make informed decisions from the early design stages. In this study, a DSS is developed that combines BIM, VPL and TPL to identify the optimal wall stratigraphy for the building envelope. The process is structured into sequential phases, in which Autodesk Revit v2026.06.24.01, Dynamo v.3.6.1 and Python v3.9 are integrated within an end-to-end workflow. In the first phase, wall stratigraphies are modelled in BIM, and parametric variations in layers are allowed alongside customisation of the material database. In the second phase, an automated workflow calculates a set of indicators covering thermal performance, environmental assessments (LCA, MRc2 LEED and mandatory national requirements), and economic evaluations (LCC). In the third phase, indicators are imported into an automated Dynamo-based MCDM, where a hybrid AHP/PROMETHEE analysis is applied and results are directly integrated into BIM, thereby supporting sustainability-focused decisions. The tool is validated on different sustainable wall stratigraphies in warm-climate contexts. The hybrid solution is ranked first, followed by rammed earth, while platform frame and X-LAM are ranked lower.

**Keywords:** building information modelling; visual programming language; text-based programming language; green public procurement; life cycle assessment; life cycle cost; multi-criteria decision-making; analytical hierarchy process; decision support system; building envelope; sustainable design; green buildings; parametric design

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## 1. Introduction

The environmental impact of the construction industry is widely acknowledged as a major challenge in the modern built environment. It consumes large amounts of energy and produces significant emissions throughout the entire life cycle of buildings, from extracting raw materials to disposal at the end of their life [1]. Construction materials and components are particularly influential in this impact, affecting multiple aspects: the extraction process is often energy- and resource-intensive, transportation involves emissions that vary based on distance and logistics, site practices impact waste and operational efficiency and manufacturing processes contribute substantially to embodied energy and greenhouse gases [2]. Consequently, materials and components choice is a strategic approach to enhance environmental performance [3], particularly when assessed at the component level, where material combinations directly determine overall environmental performance.

This context emphasises the growing need to promote sustainability within the AEC (Architecture, Engineering, Construction) sector, driven by increasingly strict regulations at both energy and environmental levels [4].

Globally, initiatives like the United Nations 2030 Agenda for Sustainable Development and Sustainable Development Goals [5], along with guidance from the International Energy Agency (IEA) [6], prioritise improving energy efficiency in buildings. In Europe, this commitment manifests in binding directives such as the Energy Performance of Buildings Directive (EPBD) [7], which establishes and progressively tightens minimum energy performance standards, supported by the "Fit for 55" package and the European Green Deal [8]. Italy incorporates these European regulations into national law through Ministerial Decree 28 October 2025 (D.M. 28 October 2025) [9], published in the Official Gazette on 5 December 2025 and effective from 3 June 2026. The update revises calculation methods, envelope standards and reference-building parameters to align national practices with EPBD III and anticipate EPBD IV, directly influencing the selection of materials and components for building envelopes.

At the environmental level, sustainability is increasingly understood through life-cycle thinking, which evaluates materials' environmental impact across their entire lifespan, as advocated by the ISO 14040 [10] series globally. European standards such as EN 15978 [11] and EN 15804 [12] support Life Cycle Assessment (LCA) methods for construction products and buildings. Voluntary certification systems like Leadership in Energy and Environmental Design (LEED) [13] also assess material impacts, working in tandem with the Construction Products Regulation (CPR) [14] and the EU Taxonomy for Sustainable Activities [15]. In Italy, environmental sustainability is further reinforced by the Minimum Environmental Criteria (CAM) [16], which establish specific material requirements for public procurement and green building practices, positioning construction materials as a key focus of environmental regulation. The CAM system was updated with Ministerial Decree 24 November 2025 (D.M. 24 November 2025), published in the Official Gazette on 3 December 2025, and effective from 2 February 2026. This decree replaces the 2022 version, introducing stricter material standards, including minimum recycled-content thresholds for structural steel and concrete, that align with the CPR and the "Do No Significant Harm" (DNSH) principle [17].

In addition to energy and environmental factors, economic considerations are crucial because they influence whether sustainable design choices and goals can be implemented in practice [18]. Even if technically and environmentally optimal solutions are identified, their widespread adoption is often limited by budget constraints and the need to demonstrate long-term economic viability to stakeholders [19]. Life cycle costing (LCC) assesses costs throughout a building component's entire life, including initial investment, maintenance, operation, replacement and end-of-life expenses. This methodology is globally standardised by ISO 15686-5 [20] and supported in Europe by EN 16627 [21], which defines a uniform calculation method aligned with environmental assessments like EN 15978 [22]. Additionally, LCC is increasingly seen as complementary to LCA, since environmentally friendly materials typically involve higher upfront costs that pay off over time [23].

Given the numerous thermal, environmental and economic criteria that must be considered simultaneously, multi-criteria decision-making (MCDM) methods are increasingly used [24]. Traditionally, assessments relied on manual processes in which data were extracted, calculated and weighted across various tools and spreadsheets. These manual methods are known to be time-consuming and prone to errors because data often transfer between disconnected platforms, raising the risk of inconsistencies and undermining the assessment's reliability [25]. Additionally, manual workflows are less suitable for the itera-

tive nature of sustainable design, which involves comparing and refining multiple design options to find the best solution [26].

Therefore, a digital transition is becoming a key strategy in the construction sector to automate, standardise and integrate data-heavy processes within unified digital platforms [27]. Among these digital tools, Building Information Modelling (BIM) is recognised as an enabling digital technology. It is defined as a digital approach through which building components are modelled within a parametric, information-rich environment, in which material properties, performance data and quantities are simultaneously managed [28]. For this reason, BIM is regarded as valuable for material selection processes. Its effectiveness is further increased when it is combined with Visual Programming Language (VPL), as is achieved [29]. This integration creates automated, interoperable workflows that facilitate data exchange between modelling, computational, and analytical platforms, thereby promoting more efficient and scalable decision-making in sustainable building envelope design [30].

A critical review of previous studies combining BIM and MCDM reveals several gaps (see Section 2). First, there is significant heterogeneity in the MCDM methods used, with no single approach considered universally optimal. This limits comparability across studies and makes method choice context-dependent. Second, the indicators used are rarely comprehensive, with many studies focusing on only one sustainability aspect, thus hindering a true multi-dimensional and holistic assessment. Third, most studies calculate indicators and perform weighting and ranking manually or through external tools outside BIM, which becomes increasingly time-consuming, error-prone and less scalable as indicators grow, restricting their use in complex, multi-criteria design tasks. Lastly, some studies lack application to real case studies, reducing the reliability and reproducibility of their results. Collectively, these gaps highlight the need for an automated and iterative MCDM framework within a single BIM-native computational environment.

Building on these gaps, this study introduces an automated, BIM-native workflow to compare external wall stratigraphy options, aimed at identifying the best solution for warm climates and supporting designers from the earliest design stages. In the proposed workflow, stratigraphy alternatives and a set of thermo-physical, environmental and economic indicators are modelled in Autodesk Revit through a customised material database. Indicators are subsequently calculated and refined within Dynamo before being processed through a parametric hybrid AHP/PROMETHEE analysis that produces the final ranking of alternatives.

Data exchange between Revit and Dynamo, and the reintegration of results into BIM, are automated through Python nodes, ensuring interoperability across all software environments. By integrating parametric modelling, VPL and TPL, the resulting end-to-end workflow displays results directly in Revit and removes the delays and errors typically linked to manual data transfer between tools. Weighting and ranking algorithms are embedded within the same system, enabling MCDM analyses to be rapidly re-run as input criteria, weights or design parameters change. Through this digitalisation, MCDM analysis is transformed from a static, one-off evaluation into a continuous and adaptable process, providing designers with a dynamic and iterative sustainability assessment tool.

The article is organised as follows: Section 2 conducts a gap analysis of previous related studies. Section 3 outlines the methodology, describing each phase involved in parameter calculation, as well as the weighting and ranking of stratigraphy solutions. Section 4 presents the results from applying the tool to the wall stratigraphies in the case study. Section 5 positions this research within the existing literature, discusses its limitations and suggests future research directions. Lastly, Section 6 offers the conclusions.

## 2. Gap Analysis of Related Previous Studies

Table 1 summarises key studies that integrate BIM and MCDM approaches for sustainability-focused decision-making in construction. It details the MCDM methods used, the indicators considered, the tools and software applied, and any case studies used for validation. Building on this overview, the following paragraph provides a critical analysis of these studies, highlighting main gaps that justify the development of the framework presented in this study.

**Table 1.** Summary of related previous studies integrating BIM and MCDM approaches for sustainability-oriented decision-making in the construction sector. In the "Tool/Software Used" column, bold text distinguishes the tools used for indicator calculation from those used for the weighting and final ranking process.

| Ref. | MCDM Method | Considered Indicators | Tool/Software Used * | Case Study |
|---|---|---|---|---|
| [31] | Fuzzy Analytic Hierarchy Process (FAHP). A combination of AHP (weights obtained through pairwise comparisons) and fuzzy logic (qualitative scores under conditions of uncertainty) | Compatibility, Durability, Traceability, Cultural Value | **For indicator calculation:** a Manual Process is used<br><br>**For the weighting and final ranking process:** a Manual Process is used | Two deteriorated historic buildings in the Agri Valley, Appennino Lucano Regional Park (Basilicata, Italy) are examined: a building in the historic centre of Gallicchio and a building in the ancient village of Il Casale in Armento. The materials evaluated are stone masonry, timber floors, and a clay-tile roofing system |
| [32] | Analytic Hierarchy Process (AHP) | Periodic Thermal Transmittance, Surface Mass, Material Purchase Cost, Compliance with CAM, LEED MRc1 Building Life Cycle Impact Reduction | **For indicator calculation:** Autodesk Revit v2025.3, Dynamo v2.19.4, Microsoft Excel (Office 365), and Tally v2025.06.24.01 (LCA plug-in for Revit)<br><br>**For the weighting and final ranking process:** Autodesk Revit v2025.3 and Dynamo v2.19.4 | An external platform-frame wall is examined, with three thermal insulation alternatives compared: Rock Wool, EPS, and Aerogel set within a Mediterranean climate context |
| [33] | Weighted Sum Model (WSM) | Economic Cost, Global Warming Potential, Embodied Energy and Acoustic Insulation | **For indicator calculation:** Autodesk Revit (v2023), Dynamo (v2.13), and ECHO<br><br>**For the weighting and final ranking process:** Microsoft Excel (Office 365) and Manual Process | 24 wall configurations are analysed (8 base stratigraphies × 3 insulation materials, plus one variant with EPS), applied to a simplified building model located in a Mediterranean climate |
| [34] | Analytical Network Process (ANP), an extension of AHP based on expert judgments according to the Saaty scale | Design Optimisation, Integrative Design, Reduced Material Need, Minimise Wastage, Integrated Project Delivery, Effective Teamwork | **For indicator calculation:** a Manual Process is used<br><br>**For the weighting and final ranking process**: a Manual Process is used | No case study implementation is presented |

**Table 1.** *Cont.*

| Ref. | MCDM Method | Considered Indicators | Tool/Software Used * | Case Study |
| --- | --- | --- | --- | --- |
| [35] | Weighted Aggregated Sum Product Assessment method with grey attribute scores (WASPAS-G) | Project preparation and coordination, construction duration, number of employees, building lifespan, adaptability to current needs, energy efficiency class, $CO_2$ emissions, waste prevention, removal of contaminated soil and materials, preservation of historic value, investments; Net Present Value (NPV), payback period, profitability; average rate of return and Internal Rate of Return (IRR) | **For indicator calculation:** a Manual Process is used.<br><br>**For the weighting and final ranking process:** a Manual Process is used | The former "Matas" measuring equipment repair factory, located in Vilnius (Lithuania), is examined; three redevelopment alternatives are compared: 1) renovation/adaptation while retaining the original use, 2) conversion into loft-type housing, 3) demolition and new construction |
| [36] | Not specified | No defined list of decision-making indicators/criteria is provided in the document | **For indicator calculation:** a Manual Process is used.<br><br>**For the weighting and final ranking process:** a Manual Process is used | No case study implementation is presented |
| [37] | Delphi-BWM (Best Worst Method) is applied. The Delphi technique is used to gather expert consensus, while BWM is used to calculate the relative weights of the criteria | Government Value, Technical Effectiveness, Business Value | **For indicator calculation:** a Manual Process is used.<br><br>**For the weighting and final ranking process:** a Manual Process is used | No case study implementation is presented |
| [38] | Analytic Hierarchy Process (AHP) | Global Warming (kg $CO_2$e), Ozone Depletion (kg CFC11e), Acidification (kg SO2e), Eutrophication (kg Ne), Formation of Tropospheric Ozone (kg O3e), Depletion of Non-Renewable Energy (kWh/MJ), Social Cost of Carbon (USD/kg $CO_2$) | **For indicator calculation:** Autodesk Revit (version 2023.1.3) and OneClick LCA (Revit plug-in, version 0.27.3, database version 7.6)<br><br>**For the weighting and final ranking process:** a Manual Process is used | A single-family housing project located in Nanaimo, British Columbia, Canada, is examined, developed from data provided by a prefabricated housing company. Three design scenarios are compared: Steel 1 (conventional hot-rolled structural steel, with XPS insulation and aluminium window frames), Steel 2 (cold-rolled recycled structural steel, with more circular materials), Timber (solid timber structure used in place of steel) |
| [39] | Variable Fuzzy PROMETHEE based on the integration of Fuzzy Set Theory, Variable Fuzzy Sets (VFSs) theory, and PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) | Technical Reliability, Ease of Operation & Maintenance, Initial Cost, Payback Period, Potential for Operational Carbon Reduction | **For indicator calculation:** Autodesk Revit, eQUEST, and EnergyPlus are used for energy simulation; Low-Impact Design Explorer (LIDX) is used for initial cost estimation (IC), Open Studio<br><br>**For the weighting and final ranking process:** MATLAB | A real commercial building in Hong Kong ("Project A") is examined, 48 m above ground level, comprising three office towers, a shopping-mall podium, and a skywalk podium, with a total floor area of 47,340 $m^2$ |

**Table 1.** *Cont.*

| Ref. | MCDM Method | Considered Indicators | Tool/Software Used * | Case Study |
| --- | --- | --- | --- | --- |
| [40] | TOPSIS-Fuzzy (Technique for Order Preference by Similarity to Ideal Solution, in its fuzzy version using trapezoidal numbers) | Global warming, ozone depletion, acidification, eutrophication, smog potential, weighted resource), Energy & Atmosphere, Material & Resources, Cost, Investment Criteria, Time, Construction Issue; Indoor Environmental Quality, Design and Architecture Issues | **For indicator calculation:** Autodesk Revit, Green Building Studio (GBS) **For the weighting and final ranking process:** MATLAB is used | A real 11-story office building in Vancouver, Canada, is examined, with a capacity of approximately 400 people, a site area of 1512 $m^2$, and a gross floor area of 2949 $m^2$, comprising public, semi-public and private functions |

* Software versions are reported in the table only where explicitly stated in the source paper; in all other cases, the software is indicated without version specification.

The analysis shows variation in the MCDM methods used for sustainability-focused decision-making in construction. No single method is preferred, as the choice depends heavily on the specific decision context. Bernardo et al. [31] used a Fuzzy Analytic Hierarchy Process (FAHP) within a Building Heritage Material Passport (BHMP) framework, where indicators such as Compatibility and Durability, along with heritage-related factors like Traceability and Cultural Value, are scored on a fuzzy scale and combined into a total score. This score is compared to a threshold ($\tau = 3.5$) to decide if historic materials should be conserved or reused. The framework was tested on two ageing historic buildings in Italy's Agri Valley, with assessments of stone masonry, timber floors and clay roofs, and a sensitivity analysis confirmed classification reliability. Parisi et al. [32] applied the classical AHP method within a fully BIM-integrated workflow in Autodesk Revit and Dynamo. They automatically calculated indicators such as thermal performance (transmittance, surface mass), environmental sustainability (CAM compliance, LEED MRc1 from LCA via the Tally plugin), and cost, then weighted these directly in Dynamo, testing on a platform-wall with different insulation options. EPS was identified as the best choice, with a ranking stable within a $\pm 10\%$ weight variation. Cascone et al. [33] also used a BIM-based parametric model, employing the Weighted Sum Model (WSM) to evaluate cost, global warming potential, embodied energy and acoustic insulation across 24 wall designs in a Mediterranean climate. They found that rammed-earth walls insulated with hemp fibre or cork offered the best performance, with a potential 80–90% reduction in design iterations.

Beyond the fully BIM-integrated applications outlined earlier, some studies utilise different MCDM methods where the multi-criteria logic remains separate from an automated BIM workflow. Haruna et al. [34] employ the Analytical Network Process (ANP) to analyse the relationships among design, construction, and management criteria, deriving weights from expert questionnaires based on the Saaty scale, not from BIM calculations, and they do not present a case study. Pavlovskis et al. [35] use the Weighted Aggregated Sum Product Assessment with grey scores (WASPAS-G) to evaluate a building redevelopment scenario involving technological, environmental, and economic sub-criteria such as NPV, payback period, and IRR, comparing refurbishment, conversion, and demolition options for a former factory in Vilnius, with all calculations and weightings done manually. Li et al. [36] propose a preliminary Design Decision Support System (DDSS) for Additive Manufacturing in Construction, which conceptualises an a posteriori MCDM approach but does not define a specific method, indicator set, or case study, as it is an early stage of a four-year research project. Naji et al. [37] use a hybrid Delphi–Best Worst Method (Delphi-BWM), assigning weights to fifteen sustainability benefits grouped into Government Value, Business

Value, and Technical Effectiveness entirely via expert consensus, without any BIM-based computation or working application.

Three additional studies reveal a different scenario where BIM is used solely as a modelling or data extraction tool, with the MCDM weighting and ranking processes conducted outside the BIM environment. Namaki et al. [38] apply traditional AHP to weigh environmental indicators from LCA and a Social Cost of Carbon metric, using data from the OneClick LCA plugin for Revit. However, their AHP weighting is done manually through expert questionnaires, independent of the BIM model, to compare scenarios involving conventional steel, recycled steel, and timber for a single-family house in Canada. Chen et al. [39] develop a Variable Fuzzy PROMETHEE model that combines Fuzzy Set Theory and Variable Fuzzy Sets with PROMETHEE to rank low-carbon building measures based on technical, economic, and environmental criteria. BIM (Revit) is connected to energy simulation tools like eQUEST and EnergyPlus for data generation, but the MCDM logic is implemented externally in MATLAB, applied to a commercial building in Hong Kong. Similarly, Fazeli et al. [40] use a Fuzzy TOPSIS approach to select sustainable building components, such as doors and windows, across environmental, economic, and social criteria. Although custom C# plug-ins link Revit with the decision-making process, the TOPSIS calculations are performed externally in MATLAB, not natively within BIM. Their framework, validated on an eleven-story office building in Vancouver, reported a 25% reduction in energy and life cycle costs. In all three cases, BIM functions primarily as a data provider, while the core multi-criteria decision-making stays external and non-interoperable with BIM.

This overview highlights a further gap concerning the indicators considered. While some works integrate thermal, environmental and economic dimensions to a considerable degree [32,33,38], others remain confined to a single dimension, focusing exclusively on heritage- and material-related criteria [31], on process- and governance-related factors [37,40] or leaving the indicator set entirely undefined at this stage of the research [36].

A third critical gap relates to the degree of automation characterising both the calculation of indicators and the weighting/ranking procedures. Only a limited number of studies achieve a fully BIM-native and automated workflow, in which indicators are computed and weighted directly within the same parametric environment [32], in most other cases, calculation and/or weighting remain manual [31,34,35,37] or are delegated to external, non-BIM computational environments such as MATLAB [38–40], thereby limiting interoperability and scalability as the number of considered indicators increases.

Although many studies are validated through real case studies covering a range of complexities, from historic buildings [31] and residential envelopes [32,33,38] to industrial redevelopment [35] and large commercial buildings [39,40], others remain purely conceptual or methodological, without case study implementation [34,36,37].

Finally, Parisi et al. [32] and Namaki et al. [38] utilise part of the same technological tools as in this study, such as Revit, Dynamo and LCA plug-ins. However, both are methodologically more limited than this framework: Parisi et al. [32] use a single, purely compensatory AHP method with a narrower set of indicators focused on thermal, cost, CAM, and LEED MRc1 criteria, and do not perform a comprehensive LCA or LCC evaluation. Meanwhile, despite incorporating BIM-derived LCA data, Namaki et al. [38] manually perform AHP weighting via expert questionnaires outside the BIM environment.

Taken together, these gaps indicate the need for an automated and iterative MCDM framework, capable of systematically integrating holistic indicators, of embedding both indicator calculation and multi-criteria weighting and ranking within a single BIM-native computational environment and of being validated through a concrete and replicable case study. Building on the identified gaps and comparing with related studies discussed, this work's novelty lies in: (1) fully automating the entire indicator calculation and ranking

process within a single Revit–Dynamo–Python environment, requiring only Excel for intermediate data staging, (2) adopting a hybrid AHP/PROMETHEE approach that overcomes the limitations of purely AHP or WSM frameworks by employing a non-compensatory outranking logic suitable for the diverse eleven indicators, and (3) integrating thermal, environmental and economic indicators simultaneously and holistically, a combination not often seen in previous BIM-MCDM applications, especially those relying on manual or externally implemented weighting procedures.

## 3. Materials and Methods

Building on the gaps identified in Section 2, this study introduces an automated, BIM-native workflow to compare different external wall stratigraphy options via MCDM. The goal is to find the best solution for warm climates and assist designers from the initial stages of design. Figure 1 shows the steps involved in this BIM-based workflow for choosing wall stratigraphy.




**Figure 1.** Overview of the proposed BIM-MCDM workflow.

In Phase 1, the wall stratigraphy options to compare are identified alongside the set of indicators ($n$ = 11), which cover thermo-physical ($n$ = 2), environmental ($n$ = 8) and economic ($n$ = 1) performance areas (see Section 3.1). During Phase 2, these stratigraphy options are modelled within the BIM environment using Autodesk Revit v.2026.4 and the material database is customised. In Phase 3, each indicator's value is calculated using Dynamo v3.6.1 (see Section 3.2); data are also refined with the Tally plugin for Revit v2026.06.24.01 and Microsoft Excel Office 365 v2604 (see Sections 3.3.1–3.3.3). Finally, in Phase 4, a parametric script in Revit is used to conduct a hybrid AHP/PROMETHEE analysis of the stratigraphy options, resulting in the final ranking (see Section 3.4).

The data extracted from Revit, required for the Dynamo-based calculation, weighting and ranking process, as well as the subsequent reintegration of the results into the BIM environment, are automated through the use of Python nodes, described in further detail in Section 3.3.2, in order to ensure interoperability between the parametric, computational and BIM environments involved in the workflow.

This modular structure also ensures the transferability of the tool: while in this study the stratigraphy options were pre-defined and modelled from the beginning, new or alternative stratigraphic configurations can be assessed by simply updating the BIM model in Revit, without requiring any modification to the underlying Dynamo and Python scripts.

By integrating parametric modelling (Autodesk Revit), VPL (Dynamo), and TPL (Python), the computational core developed in this study enables an end-to-end BIM-MCDM workflow in which results are made visible to the designer in real time within Revit. This integration further allows the sustainability assessment process to be iterated dynamically and digitally, thereby supporting a more responsive and design-integrated decision-making process, in which alternative stratigraphic configurations can be rapidly re-evaluated as design parameters, indicator weights or boundary conditions are modified.

To support transparency and enable independent verification of the computational logic underlying the proposed workflow, the complete Python scripts are provided as the Supplementary Materials (Scripts S1–S4).

### *3.1. Phase 1: Identification of External Wall Stratigraphy Alternatives and Selection of Indicators*

Four sustainable wall stratigraphy alternatives are selected for comparison, representing a progression from massive, bio-based construction systems to lightweight and engineered timber solutions. This selection stems from an ongoing study investigating the potential of earth-based elements to increase the thermal mass of vertical envelope components, thereby enhancing their thermal performance in warm climates. Table 2 provides a summary of the analysed stratigraphies, highlighting the constituent layers and their respective thicknesses.

Stratigraphy 1 features a platform-frame wall with an internal rammed earth infill, combining the thermal mass of earth with a lightweight timber frame. It leverages the high thermal inertia of earthen materials while maintaining the benefits of platform-frame construction, which is especially beneficial in warm climates where thermal mass reduces temperature swings. Stratigraphy 2 is a platform-frame wall with an external rammed earth layer positioned on the outer face, exploring whether the placement of thermal mass affects thermal and environmental performance under warm climate conditions. Stratigraphy 3 is a standard lightweight platform-frame wall made of timber. Lastly, Stratigraphy 4 uses an X-LAM (Cross-Laminated Timber) panel, a prefabricated engineered-wood solution known for quick assembly and reduction in construction time. This option broadens the comparison by including a high-performance engineered-timber alternative alongside earth-based and conventional lightweight walls.

**Table 2.** Summary of the four analysed wall stratigraphy alternatives, showing the Identifier, Typology, constituent layers, ordered from the external to the internal side, and their thicknesses.

| Identifier | Typology | Layers from Outside to Inside | Thickness [cm] |
|---|---|---|---|
| Stratigraphy 1 | Platform frame with internal rammed earth brick | Fibre-gypsum board | 1.25 |
| | | Air cavity | 5 |
| | | Vapour barrier | 0.2 |
| | | OSB panel | 1 |
| | | Rammed earth block | 15 |
| | | OSB panel | 1 |
| | | Wood fibre insulation | 12 |
| | | High-density wood fibre insulation | 6 |
| | | External render | 1 |
| Stratigraphy 2 | Platform frame with external rammed earth board | Fibre-gypsum board | 1.25 |
| | | Air cavity | 2.8 |
| | | Rammed earth board | 2.2 |
| | | Vapour barrier | 0.2 |
| | | OSB panel | 1 |
| | | Wood fibre insulation | 12 |
| | | OSB panel | 1 |
| | | High-density wood fibre insulation | 6 |
| | | External render | 1 |
| Stratigraphy 3 | Standard platform frame | Fibre-gypsum board | 1.25 |
| | | Air cavity | 4 |
| | | Vapour barrier | 0.2 |
| | | OSB panel | 1 |
| | | Wood fibre insulation | 12 |
| | | OSB panel | 1 |
| | | High-density wood fibre insulation | 6 |
| | | External render | 1 |
| Stratigraphy 4 | X-LAM | Plasterboard | 1.3 |
| | | Fibre-gypsum board | 1.3 |
| | | Wood fibre insulation | 5 |
| | | X-LAM | 15 |
| | | High-density wood fibre insulation | 16 |
| | | External render | 1 |

This comparison ranges from earth-integrated massive systems to fully lightweight, engineered-timber solutions, aiming to identify which option provides the optimal balance of thermal, environmental and economic performance, particularly in warm climates where thermal mass and dynamic thermal behaviour significantly impact envelope design. This selection aimed to maximise constructive and material diversity within a manageable case-study set, rather than offering a comprehensive survey of all sustainable envelope systems. The four alternatives are selected to represent different points along the thermal mass spectrum, from earth-based massive construction to fully lightweight engineered timber, allowing the framework to be tested across a range of envelope strategies.

In Phase 1, the indicators used to evaluate the stratigraphies are also selected. The chosen indicator set comprises eleven indicators, covering three thematic performance areas: thermo-physical ($n$ = 2), environmental ($n$ = 8) and economic ($n$ = 1). The complete set of indicators organised according to their thematic area, cluster and assessment method, is summarised in Table 3.

**Table 3.** Indicators considered for the thermal, environmental and economic evaluation of the analysed wall stratigraphies in warm-climate contexts.

| Thematic Area | Cluster | Indicators | Assessment Method |
|---|---|---|---|
| Thermal | Thermo-physical performance according to D.M. 28 October 2025 | Periodic Thermal Transmittance<br>Surface Mass | $Y_{IE} \leq 0,1$<br>$M_s \geq 230$ |
| Environmental | LCA | Global Warming Potential (GWP)<br>Ozone Depletion Potential (ODP)<br>Acidification Potential (AP)<br>Eutrophication Potential (EP)<br>Photochemical Ozone Creation Potential (POCP)<br>Abiotic Depletion Potential (ADP) | Calculation of values |
| | CAM verification according to D.M. 28 October 2025 | CAM Compliance | Compliance with CAM Sections 2.4.1, 2.4.6, 2.4.7 and 2.4.8 * |
| | LEED Score | MRc2 Reduced Embodied Carbon | $\Delta GWP\% \geq 10\%$ |
| Economic | LCC | Construction Costs and Maintenance Costs | Calculation of values |

* Sections 2.4.1, 2.4.6, 2.4.7 and 2.4.8 refer to the corresponding sections of the CAM (Minimum Environmental Criteria) regulation, and not to sections of this paper.

Regarding the two thermo-physical indicators, the periodic thermal transmittance and the surface mass, they must both meet the standards set by D.M. 28 October 2025 [9]. This decree establishes the minimum performance criteria for building envelopes to ensure sufficient thermal comfort, specifically setting a maximum threshold of 0.10 W/(m$^2$·K) for the periodic thermal transmittance and a minimum threshold of 230 kg/m$^2$ for the surface mass values that apply specifically to Mediterranean climate contexts. The periodic thermal transmittance evaluates how the wall responds dynamically to summer thermal loads, calculated according to UNI EN ISO 13786 [41], as mandated by the decree:

$$Y_{IE} = \frac{|\hat{q}_{IE}|}{|\hat{\theta}_e|}, \quad (1)$$

where $Y_{IE}$ is the periodic thermal transmittance [W/(m$^2$·K)], $\hat{q}_{IE}$ is the amplitude of the internal heat flux density [W/m$^2$] and $\hat{\theta}_e$ is the amplitude of the external air temperature variation [K]. Also, surface mass is used to estimate the opaque element's capacity to store heat and contribute to the building's thermal stability and, in compliance with D.M. 28 October 2025 [9], is calculated according to the UNI EN ISO 13786 [41] standard:

$$M_s = \sum_{i=1}^{n} \rho_i d_i, \quad (2)$$

where $M_s$ is the surface mass [kg/m$^2$], $\rho_i$ is the density of layer i [kg/m$^3$] and $d_i$ is the thickness of layer i [m].

The environmental indicators are articulated as follows: six relate to the LCA across different impact categories, one concerns CAM verification in accordance with the D.M. 24 November 2025 [16], and one addresses the LEED v5 score for credit MRc2 within the Materials and Resources (MR) category [42].

Concerning the LCA cluster, the evaluated indicators encompass six environmental impact categories: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), and Abiotic Depletion Potential (ADP). These categories are chosen because, according to the LCA methodology outlined in standards EN 15804 and

EN 15978 [11,12], they form the core impact indicators that thoroughly characterise the environmental performance of construction materials during their production and use phases. Including these indicators in the MCDM analysis allows assessment not only of climate change contribution (GWP), often the most reported metric, but also of other frequently overlooked environmental effects, such as ozone layer depletion, soil and water acidification, aquatic eutrophication, photochemical smog formation, and depletion of non-renewable resources. It should be noted that these six impact categories are not assigned individual weights in the AHP/PROMETHEE ranking process. Instead, they are combined into a single composite LCA criterion in the pairwise comparison matrix (Section 3.4), which is assigned one overall weight along with the other six criteria. This setup ensures the environmental dimension is not implicitly overemphasised compared to the thermal and economic dimensions in the final ranking.

The CAM constitute a set of mandatory environmental requirements introduced in Italy to promote a Green Public Procurement (GPP) approach within the construction sector, requiring building materials and products to meet specific environmental, health-related and circularity criteria, differentiated according to product category. About the CAM indicator, the materials composing the four stratigraphies are required to be verified against the specific reference categories established by D.M. 24 November 2025 [16]. Specifically, the fibre-gypsum board and the plasterboard are assessed under category 2.4.8 Partitions, perimeter counter-walls and dry suspended ceilings, the OSB panel and the X-LAM panel are assessed under category 2.4.6 Wood-Based and Wood Products, the wood fibre insulation and the high-density wood fibre insulation are assessed under category 2.4.7 Thermal and Acoustic Insulation Materials, while the external render is assessed under category 2.4.1 Indoor Pollution. Conversely, the rammed earth block, the rammed earth board, the vapour barrier and the air cavity do not fall within the scope of application of the CAM decree and are therefore excluded from this specific verification.

The LEED cluster focuses on the MRc2 reduce embodied carbon credit, part of the Materials and Resources (MR) category in the LEED v5 BD+C: New Construction system [42]. This credit mandates that the proposed stratigraphy achieves at least a 10% reduction in Global Warming Potential (GWP) compared to a baseline stratigraphy, calculated according to Equation (3):

$$\Delta GWP\% = \frac{GWP_{base} - GWP_{alt}}{GWP_{base}} \cdot 100 \geq 10\%, \quad (3)$$

where ΔGWP% is the percentage reduction in Global Warming Potential, $GWP_{base}$ is the Global Warming Potential of the baseline stratigraphy [kg $CO_2$eq/$m^2$], and $GWP_{alt}$ is the Global Warming Potential of the proposed stratigraphy alternative [kg $CO_2$eq/$m^2$]. In this study, the baseline is identified as Stratigraphy 1. Stratigraphy 1 is selected as the baseline because it features the internal rammed earth block, the most established construction method among the four options. Of the four systems analysed, this internal rammed-earth setup is the most conventional and well-documented way to combine thermal mass with a timber platform-frame, aligning with LEED v5 MRc2 requirements that the baseline reflect standard construction practices rather than innovative or less common methods. The other configurations, namely external rammed earth (Stratigraphy 2), lightweight platform-frame (Stratigraphy 3), and engineered X-LAM panels (Stratigraphy 4), each introduce different variations, such as the placement of thermal mass, lack of massive components or fully engineered timber structures. Therefore, Stratigraphy 1 serves as the reference case for assessing the environmental performance of the other stratigraphies, following standard LEED approaches to establish a typical conventional baseline for comparison. Credits are awarded based on the percentage of GWP reduction relative to the baseline: two points are given for meeting baseline or average reference values. Points increase up to six as the

GWP reduction reaches or exceeds 40%, with intermediate thresholds corresponding to intermediate points, up to a maximum of six points for this credit.

Finally, the economic performance of the stratigraphy alternatives is assessed through an LCC evaluation, extended over a reference time horizon of 60 years. This analysis integrates two main cost components: (1) construction costs, corresponding to the economic burden associated with the supply and installation of materials and (2) maintenance costs, corresponding to expenses related to future scheduled interventions (e.g., restoration of the external render). Maintenance costs are calculated by applying the Present Value (PV) formula, through which future cash flows are discounted using a fixed discount rate of 3%.

### *3.2. Phase 2: BIM and Structuring of the Customised Material Database*

In the second phase, the four stratigraphies outlined in Section 3.1 are modelled using Autodesk Revit. This software is chosen as the primary BIM authoring tool because of its widespread use in industry and academia, its built-in support for parametric wall assembly modelling and its strong compatibility with VPLs like Dynamo. These features are key for automating the indicator computation and MCDM analysis in later steps. Additionally, Revit enables the direct inclusion of detailed material properties, layer-specific data and custom parameters within the BIM, facilitating seamless and bidirectional data flow between the geometry and the computational workflow.

To support the modelling process and the subsequent automated MCDM analysis (Sections 3.3 and 3.4), the material database is customised, extending the default Revit material library with the specific products, layers and technical properties required by the four stratigraphy alternatives. This customisation of the material database is regarded as a key step within the overall workflow, as it ensures that all the data required for the automated, Dynamo-based calculation of thermal, environmental and economic indicators are natively available and consistently structured within the BIM environment, thereby avoiding the need for external data sources or manual data entry during the subsequent computational phase.

Tables 4–8 present the set of BIM parameters linked to the thermo-physical, environmental, and economic performance cluster, organised into seven descriptive fields. The "Parameter Name" indicates the specific parameter considered within BIM. The "Level of Assignment" shows whether the parameter is allocated at the material level or the wall (assembly) level. The "IN/OUT Parameter" field states if the parameter serves as an input for subsequent calculations (Section 3.3) or as an output from the process. The "Parameter Creation Method" indicates whether the parameter is native to Autodesk Revit or created using tools like Dynamo or Python (Section 3.3). The "Parameter Population Method" describes whether the parameter value is manually entered or automatically generated via a parametric workflow. The "Data Source" identifies whether the value originates from product datasheets or is produced through parametric processes such as Dynamo or Excel. Lastly, the "Data Type" specifies the format of the parameter within the BIM model, such as Number, Boolean or Text.

**Table 4.** BIM parameters associated with the thermo-physical performance indicators (D.M. 28 October 2025), including assignment level, parameter type, creation and population methods, data source and data type.

| Parameter Name | Level of Assignment | IN/OUT Parameter | Parameter Creation Method | Parameter Population Method | Data Source | Data Type |
|---|---|---|---|---|---|---|
| Thermal Conductivity (W/(m·K)) | Material (All) | Input | Existing in Autodesk Revit | Manual | Product Datasheet | Number |
| Density (kg/m$^3$) | Material (All) | Input | Existing in Autodesk Revit | Manual | Product Datasheet | Number |
| Specific Heat Capacity (J/(kg·K)) | Material (All) | Input | Existing in Autodesk Revit | Manual | Product Datasheet | Number |
| Thickness (m) | Material (All) | Input | Existing in Autodesk Revit | Manual | Parametric (Dynamo/Excel) | Number |
| Compliance with D.M. 28 October 2025 | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo) | Text |

**Table 5.** BIM parameters associated with the environmental performance indicators (LCA impact categories), including assignment level, parameter type, creation and population methods, data source and data type.

| Parameter Name | Level of Assignment | IN/OUT Parameter | Parameter Creation Method | Parameter Population Method | Data Source | Data Type |
|---|---|---|---|---|---|---|
| Global Warming Potential (kg$O_2$eq) | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo/Tally) | Number |
| Ozone Depletion Potential (CFC-11eq) | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo/Tally) | Number |
| Acidification Potential (KgNeq) | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo/Tally) | Number |
| Eutrophication Potential (Kg$O_2$eq) | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo/Tally) | Number |
| Photochemical Ozone Creation Potential (kg $C_2H_4$eq) | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo/Tally) | Number |
| Abiotic Depletion Potential (kgSbeq) | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo/Tally) | Number |

**Table 6.** BIM parameters associated with the environmental performance indicators (CAM compliance), including assignment level, parameter type, creation and population methods, data source and data type.

| Parameter Name | Level of Assignment | IN/OUT Parameter | Parameter Creation Method | Parameter Population Method | Data Source | Data Type |
|---|---|---|---|---|---|---|
| Compliance with UNI EN 16516 or UNI EN ISO 16000 or EN 717-1 | Material (CAM Section 2.4.1 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Compliance with minimum loading factors | Material (CAM Section 2.4.1 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Specific verification of DBP and DEHP content | Material (CAM Section 2.4.1 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Presence of certifications/labels recognised by CAM | Material (CAM Section 2.4.1 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Compliance with sustainable/responsible forest origin | Material (CAM Section 2.4.6 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Absence of SVHC | Material (CAM Section 2.4.7 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |

**Table 6.** *Cont.*

| Parameter Name | Level of Assignment | IN/OUT Parameter | Parameter Creation Method | Parameter Population Method | Data Source | Data Type |
|---|---|---|---|---|---|---|
| Presence of CE and DoP | Material (CAM Section 2.4.7 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Compliance with safety specifications | Material (CAM Section 2.4.7 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Blowing agent content below 6% | Material (CAM Section 2.4.7 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Absence of lead-based catalysts | Material (CAM Section 2.4.7 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Absence of ODP | Material (CAM Section 2.4.7 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Boolean (Yes/No) |
| Percentage of recycled and recovered material | Material (CAM Sections 2.4.7 and 2.4.8 *) | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Number |
| Compliance with D.M. 28 October 2025 | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo) | Text |

* Sections 2.4.1, 2.4.6, 2.4.7 and 2.4.8 refer to the corresponding sections of the CAM (Minimum Environmental Criteria) regulation, and not to sections of this paper.

**Table 7.** BIM parameters associated with the environmental performance indicators (LEED MRc2 credit), including assignment level, parameter type, creation and population methods, data source and data type.

| Parameter Name | Level of Assignment | IN/OUT Parameter | Parameter Creation Method | Parameter Population Method | Data Source | Data Type |
|---|---|---|---|---|---|---|
| Global Warming Potential ($kgO_2eq$) | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo/Tally) | Number |
| MRc2 LEED Point | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo) | Text |

**Table 8.** BIM parameters associated with the economic performance indicator (life cycle cost), including assignment level, parameter type, creation and population methods, data source and data type.

| Parameter Name | Level of Assignment | IN/OUT Parameter | Parameter Creation Method | Parameter Population Method | Data Source | Data Type |
|---|---|---|---|---|---|---|
| Construction Costs | Wall | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Number |
| Maintenance Costs | Wall | Input | Added (Dynamo + Python) | Manual | Product Datasheet | Number |
| LCC | Wall | Output | Added (Dynamo + Python) | Automated (Dynamo + Python) | Parametric (Dynamo) | Number |

In Table 4, the four input parameters are available in Autodesk Revit: the first three are manually populated from product datasheets, while thickness is generated parametrically. The final compliance output is newly added and fully automated via Dynamo and Python.

In Table 5, all parameters are output values, automatically populated through the parametric integration of Dynamo and the Tally plug-in, requiring no manual input. Conversely, in Table 6, all parameters except the final compliance output are input values, manually filled from product datasheets, even though they are technically introduced as new BIM parameters through Dynamo and Python. Table 7 demonstrates the highest level of automation, with both the inherited GWP value and the MRc2 LEED Point being entirely automated outputs. Lastly, Table 8 follows a pattern like Tables 4 and 6, where

construction and maintenance costs are manually entered, and the final LCC value is automatically calculated.

Tables 4–8 collectively reveal a consistent pattern across all indicator groups, centred on a clear separation between parameter creation and population. Creating new BIM parameters, whether input or output, is systematically automated in nearly all clusters, implemented through Dynamo and Python regardless of the data type. This shows that the information database is digitalised, minimising manual parameter definition in Revit. Conversely, input parameters must be manually populated when the data are qualitative, document-based, depend on external certification (as in the CAM cluster), or come from cost documentation that cannot be processed natively in a parametric system (as in the LCC cluster). This is a limitation of BIM-MCDM workflows, as such data require human judgement or external evidence. When the data are quantitative and derived from other parametric or simulation sources, like LCA impact categories calculated via Tally or the LEED MRc2 score from LCA outputs, the entire process of calculation, aggregation and integration into BIM is fully automated. This pattern, where manual effort is limited to initial data acquisition, and all further steps are automated, forms the core of the workflow. Details of the specific Dynamo and Python routines used are provided in Sections 3.3 and 3.4.

### *3.3. Phase 3: Calculation of Indicators Through VPL and TPL*

The Dynamo parametric script, enhanced with "Python nodes", automatically extracts from Revit and calculates indicator values, compares them to relevant reference thresholds when needed and reintegrates the data into the BIM environment.

#### 3.3.1. Automated Data Extraction from Autodesk Revit

The entire process centres on an automated data extraction method that is consistently repeated for each of the four wall stratigraphies (Figure 2). In the External Wall group, a wall element is initially selected from the Revit model using the "Select Model Element" node, then its wall type is obtained via the "Element.ElementType" node. The "FamilyType.CompoundStructureLayers" node is subsequently used on this wall type, breaking down the wall into its individual compound structure layers while also extracting multiple data streams for each layer. These include the materials used, their functions, widths (thicknesses), structural roles (such as core or non-core), and other layer-level properties. A "Code Block" node with the value "1" connected to an equality operator (==) is used along with the "IsCore" output to create a Boolean mask that identifies the wall's structural core, separating it from non-structural layers. This Boolean mask is then sent in parallel to three "List.FilterByBoolMask" nodes, each targeting a specific data stream: (1) the Structure group, which isolates the structural layer(s), (2) the Thickness [cm] group, filtering the layer thicknesses, and (3) the Materials group, filtering the layer materials. In each group, the filtered list from "List.FilterByBoolMask" is reversed using a "List.Reverse" node to restore the correct layer order from outside to inside of the wall, aligning with the physical stacking shown in Section 3.1. In the Materials group, the Material.Name node extracts material names from the reversed list, which are then used to query the custom material database and obtain parameters needed to calculate the thermo-physical, environmental, and economic indicators discussed in Sections 3.3.2–3.3.4.

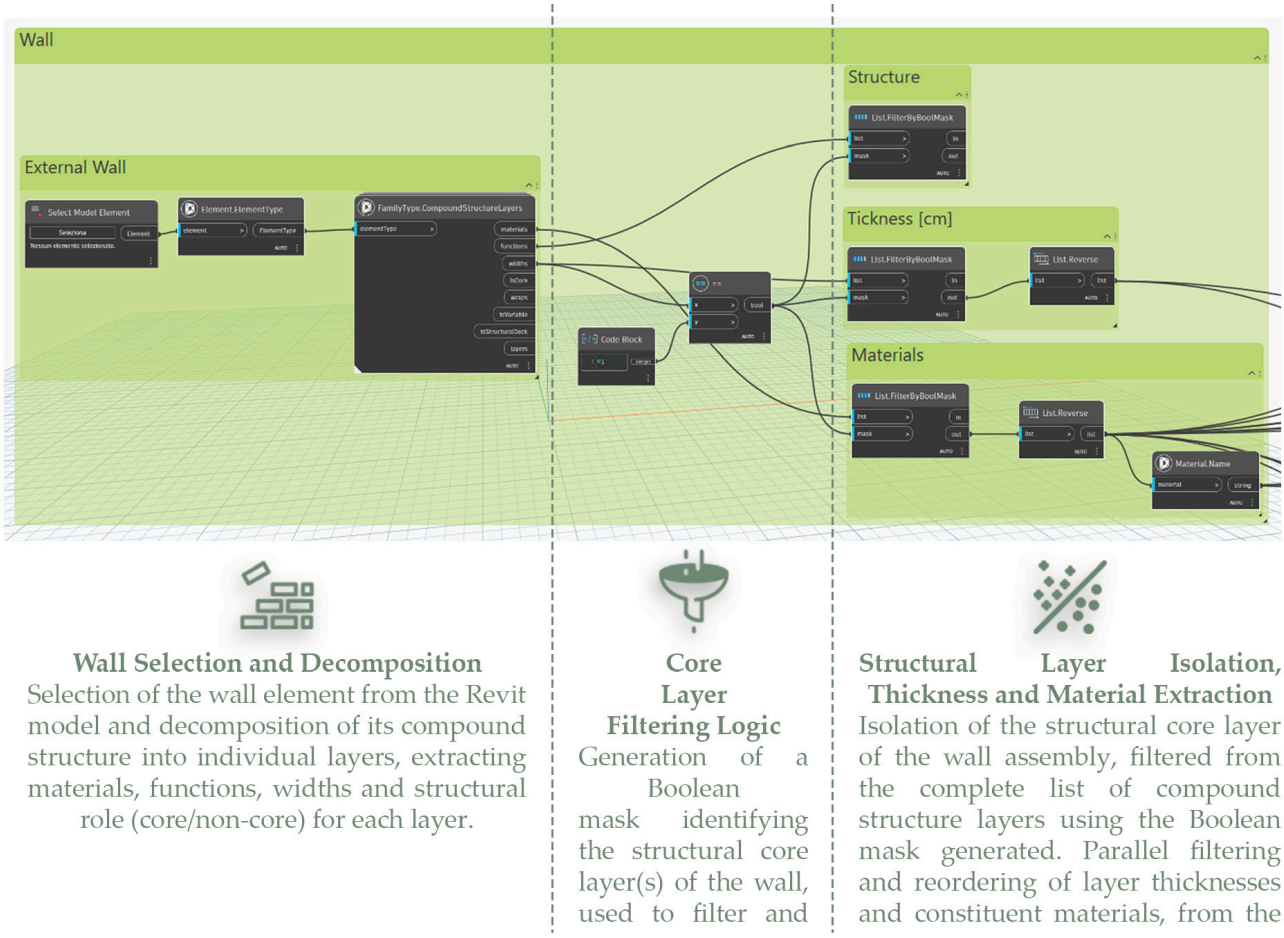



**Figure 2.** Dynamo script for the automated extraction of wall layer data (materials, thicknesses and structural role) from the Revit model.

#### 3.3.2. Calculation of Thermal Performance Indicators

Following the initial data extraction, the remaining thermal parameters required to obtain the complete set of input parameters listed in Table 4 are retrieved, and all data are subsequently transcribed into an Excel spreadsheet, which automatically calculates the periodic thermal transmittance and surface mass indicators.

The material-level thermal conductivity is obtained using the "MaterialThermalConductivity" node, applied to the previously extracted list of materials. Since specific heat and density values are not directly accessible via standard Dynamo nodes, they are retrieved through two dedicated "Python script" nodes that follow the custom extraction routines described in Figure 3. For example, the Python node automatically retrieves the specific heat capacity of one or more materials from the Revit model. It obtains each material's "ThermalAssetId" and, if available, extracts the raw specific heat stored internally by Revit. Since Revit uses internal (non-metric) units, the script automatically converts this value to the standard metric system (J/(kg·K)). It manages compatibility across different Revit versions using a try/except block, the "UnitTypeId" method for Revit 2022+ and "DisplayUnitType" for earlier versions. The final value is rounded to two decimals and returned. The script handles both single and multiple materials, with error handling that returns 0.0 if data is missing or extraction fails.

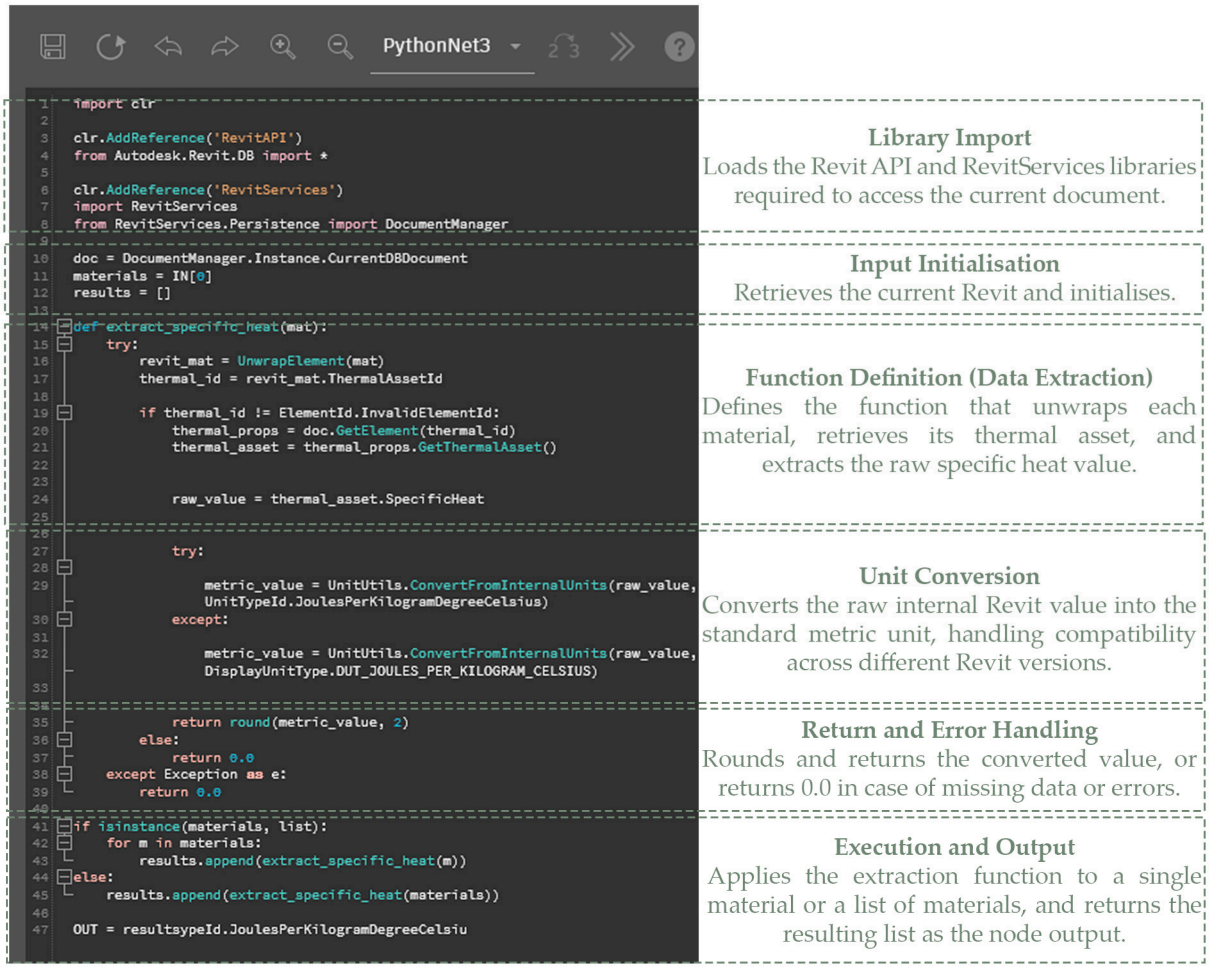



**Figure 3.** Python script for the automated extraction of the specific heat capacity from Revit materials, divided into six functional blocks. The complete script is provided as the Supplementary Materials (Script_S1_Specific_Heat_Extraction.py).

The layer-level thermal resistance is then computed using a "Code Block" node that applies a conditional rule: a fixed thermal resistance of 0.18 $m^2K/W$ is assigned to air cavity layers identified by the string "Analytical Surface—Air Surfaces." For all other layers, the thermal resistance is calculated as the thickness divided by the thermal conductivity. The final values are rounded to three decimal places using a "Math.Round" node.

The resulting parameters are then transferred to Microsoft Excel. A File Path node specifies the target spreadsheet file, while a String node identifies the specific stratigraphy being processed (e.g., "Stratigraphy 1"), ensuring that data from each of the four analysed wall configurations are written to the correct location within the workbook. The relevant thermal resistance value of air cavity layers is extracted through a "List.GetItemAtIndex" node and written to the spreadsheet through a "Data.OpenXMLExportExcel" node, configured with the target file path, sheet name, data and starting row/column coordinates. In parallel, an equality check (==) flags the presence of air cavity layers within the stratigraphy, exporting the corresponding Boolean result to a dedicated cell of the spreadsheet.

A similar export logic is replicated for thermal resistance, thermal conductivity, density, specific heat capacity, wall stratigraphy composition and layer thicknesses, each employing a combination of "List.RemoveItemAtIndex" and "List.Insert" nodes, where required, to adjust the layer sequence before export (e.g., excluding or repositioning specific layers such as air cavities), followed by a dedicated "Data.OpenXMLExportExcel" node writing the

corresponding parameter values to a specific row and column range of the spreadsheet, uniquely identified for each stratigraphy through "Code Block" indices.

This fully automated export process carefully transfers all thermo-physical input parameters from Table 4 into an Excel spreadsheet, which functions as a black-box tool to produce reliable results without direct manipulation of formulas during runtime [41,43]. The spreadsheet follows the calculation method outlined in UNI EN ISO 13786 for determining dynamic thermal properties, forming the basis for assessing the thermal performance requirements specified by Italian D.M. 28 October 2025 and ensuring consistency between the computational tool and national regulations. Using this method, the spreadsheet automatically computes the periodic thermal transmittance, Equation (1), and the surface mass, Equation (2), for each of the four wall stratigraphies.

The resulting values are re-imported into the Dynamo and compared against the thresholds established by the decree (Table 3), after which the compliance output parameter "Compliance with D.M. 28 October 2025", reported in Table 4, is automatically created and populated through a dedicated Python script.

The calculated values of surface mass, thermal transmittance and periodic thermal transmittance are first retrieved from the Excel spreadsheet through a "File Path" node, specifying the source file and a String node, identifying the relevant worksheet, connected to a "Data.OpenXMLImportExcel" node, which imports the corresponding data range into Dynamo. From the imported dataset, the required numerical values are extracted through a series of "Code Block" and "List.GetItemAtIndex" nodes, applied in parallel to isolate the individual indicator values corresponding to each stratigraphy. In parallel, the associated parameter names are extracted through an analogous sequence of "Code Block" and "List.GetItemAtIndex" nodes, subsequently concatenated through a "List.Join" node to reconstruct the complete parameter identifiers required for reintegration into the BIM environment.

The extracted values and corresponding parameter names are then used to populate the BIM model: a wall element (e.g., "Stratigraphy 1") is selected from the Revit model through the "Select Model Element" node, and the three retrieved indicator values (surface mass, thermal transmittance and periodic thermal transmittance) are written back into the corresponding BIM parameters through three parallel "Element.SetParameterByName" nodes, each linking the selected wall element to the respective parameter name and calculated value. Finally, the relevant parameter category is defined through a "Categories" node, and a dedicated Python script node is employed to automatically create and populate the output parameter reported in Table 4 (Figure 4).

This Python script automates creating and populating shared parameters in the Revit project. It begins by retrieving the current Revit document and application, then takes a list of parameter names and target categories, converting single values into lists for stability. A category set is built from these categories, and the script then opens the project's shared parameter file, creating a new one on the desktop if none exists. Inside, it retrieves or creates a group called "Project_New Parameter" to organise new shared parameters. The script loops over each parameter name: if a definition does not exist, it creates a numeric one; then, it creates an instance binding to link the parameter to the category set and adds it to the project's bindings if not already present, preventing duplication. All actions are performed within a Revit transaction, ensuring safe commit or rollback, with the status of each parameter (created or existing) returned. This process automatically generates and makes parameters accessible in the BIM model, eliminating manual input.

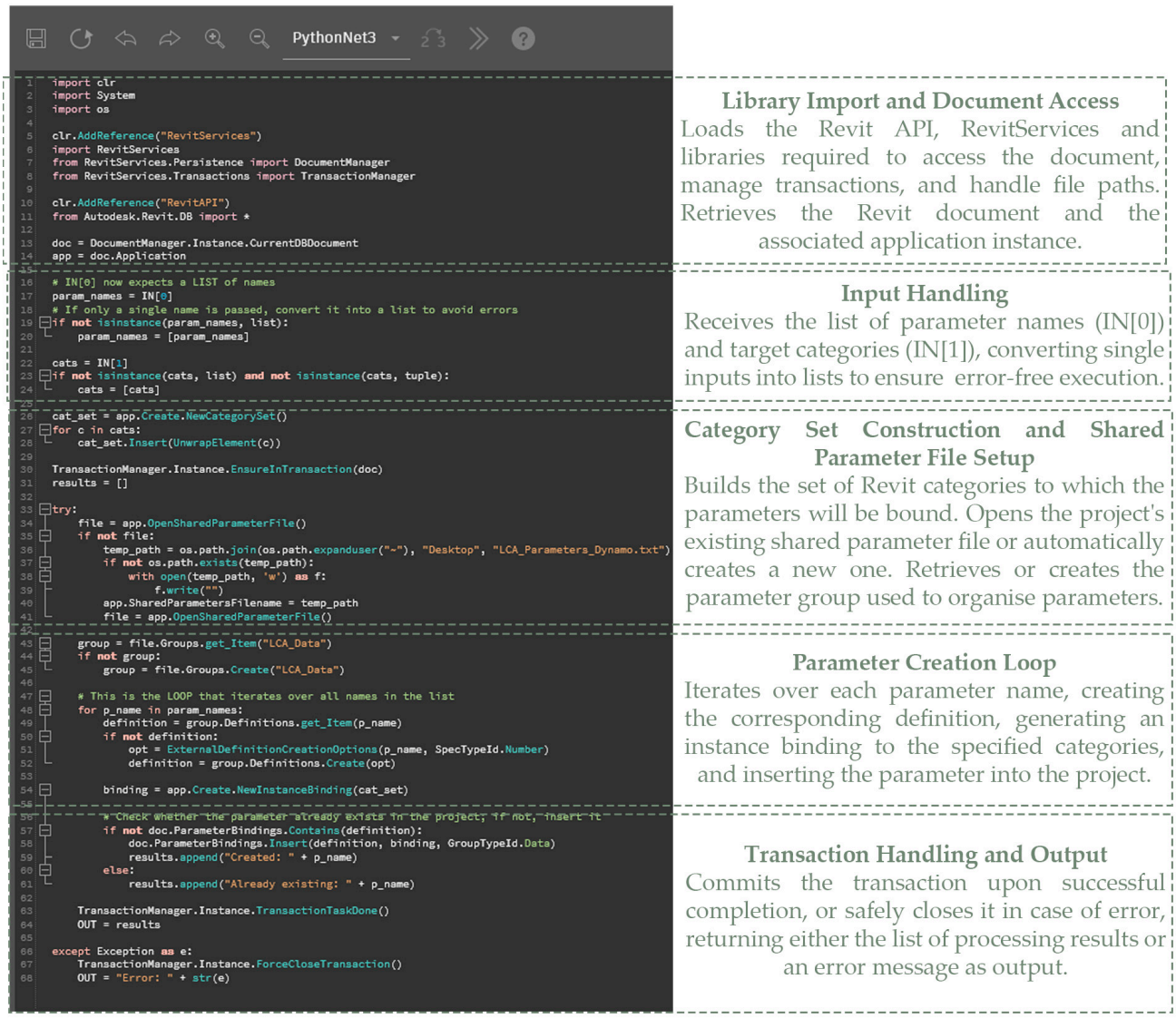



**Figure 4.** Python script for the automated creation of shared parameters within the Revit project, used to host the new shared parameter. The complete script is provided as the Supplementary Materials (Script_S2_Shared_Parameter_Creation.py).

### 3.3.3. Calculation of Environmental Indicators

Environmental indicators are calculated using Dynamo scripts (VPL) optimised with Python nodes (TPL). As highlighted in Section 3.1, these indicators include CAM compliance verification, LCA impact category calculation and LEED points assessment. For the latter two, the Tally plug-in for Revit is also required.

CAM compliance verification is carried out using dedicated Dynamo scripts, organised similarly for each material category within the four wall stratigraphies, namely external render, wood-based products, thermal and acoustic insulation materials, and dry-system partitions. Each script correlates with the relevant CAM section and uses input parameters listed in Table 6. For example, the script for verifying insulation materials, aligned with the requirements in Section 2.4.7 of the CAM decree (Thermal and Acoustic Insulation Materials), is detailed in Figure 5.

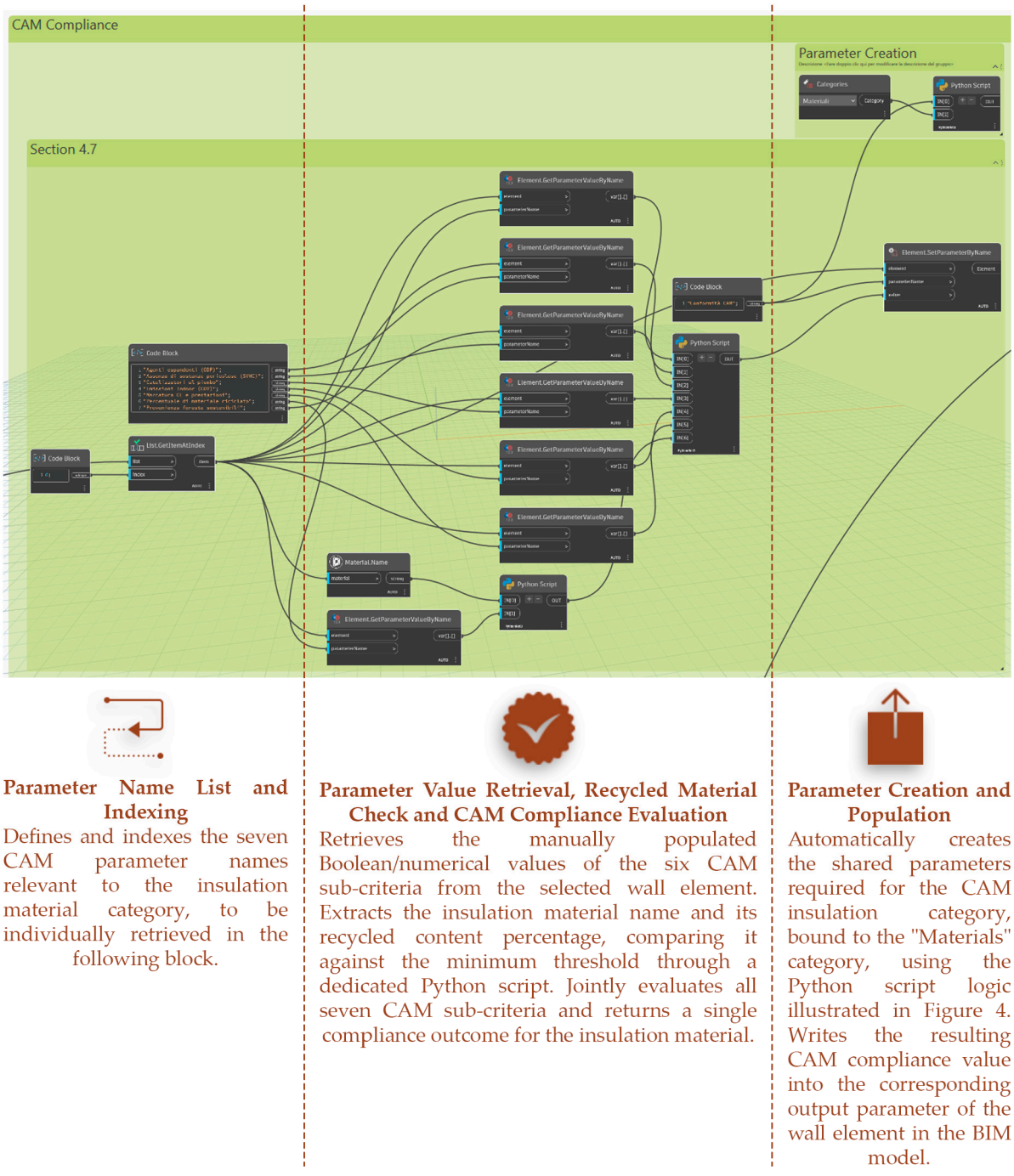



**Figure 5.** Example of the Dynamo script structure used for CAM compliance verification, shown for the insulation material category (Section 2.4.7 of the CAM decree) and replicated for the other material categories.

A "Code Block" node lists the seven parameter names needed for verification, which correspond to the input indicators in Table 6 for the insulation material category. These parameter names refer to material-level parameters previously created and made available in Revit through a Python script analogous to the one illustrated in Figure 4, following the same automated parameter creation logic described above. The names are individually fetched using a "List.GetItemAtIndex" node, with the index provided by an auxiliary Code Block. The retrieved names are then passed to six parallel "Element.GetParameterValueByName" nodes, each extracting the associated Boolean or numerical value from the selected wall element, based on the data previously entered from the

product datasheet. The "Material.Name" node extracts the insulation material's name from the wall assembly, while a second "Element.GetParameterValueByName" node retrieves the percentage of recycled material. This value, along with a threshold, is processed through a "Python Script" node, which stores the minimum recycled-content threshold associated with each insulation material typology, expressed as a percentage of the total material content, in accordance with the CAM decree. Given the specific insulation material and its declared recycled content as input, the script compares the value to the corresponding threshold and returns a compliant/non-compliant textual output, which is subsequently used, together with the remaining CAM sub-criteria, to determine the overall CAM compliance outcome for the insulation material category. The resulting parameters are then fed into another "Python script" node that evaluates all CAM sub-criteria for the insulation material category collectively and produces a single compliance result. A "Code Block" node sets the label "CAM Compliance", which, combined with the Boolean or text outcome, is used by a final "Element.SetParameterByName" node to automatically populate the CAM compliance output parameter reported in Table 6 within the wall element in the BIM model, this output parameter is, in turn, created through a "Python script" comparable to the one illustrated in Figure 4. This procedure—parameter retrieval, criterion evaluation via Python and updating BIM—is similarly applied to the other material categories, with adjustments only to the specific parameters and thresholds for each CAM section.

For calculating the impact categories required to verify the LCA indicators and the LEED MRc2 credit, the Tally plug-in for Revit is employed and integrated within the Dynamo script.

Tally is a Revit plug-in that evaluates environmental impacts of materials by directly pulling data from the BIM model. It employs a cradle-to-grave LCA system boundary, covering the product, construction, use and end-of-life stages. The assessment uses 1 $m^2$ of external wall as the functional unit, based on a 60-year building lifespan, with impacts calculated via Tally's integrated LCA database. Tally allows direct extraction of stratigraphic data and maps project materials to those in native databases such as GaBi and EPDs. Consistent with Tally's official methodology, the background database represents average conditions, with proxy datasets applied where region-specific data are unavailable. Transportation from manufacturer to construction site (module A4) is included using Tally's default average distance assumptions, while end-of-life treatment (modules C2–C4) follows average construction and demolition waste treatment rates, applying an avoided-burden approach for recycled materials and an energy-recovery credit for incinerated fractions. Tally automatically generates a Bill of Materials (BoM), showing material quantities and impacts, which updates automatically when stratigraphy, materials or geometry change. This enables ongoing impact recalculations and BIM workflow integration. Impact categories are detailed in reports exported from Tally to Excel, showing impact values over the building's life cycle. This process is repeated to produce a separate report for each of the four wall stratigraphies under review.

First, the impact category values are imported into Dynamo via dedicated parametric scripts that link Dynamo to Excel, as explained in Section 3.2. Dynamo then uses these values to automatically generate and fill the shared parameters listed in Table 5 for the LCA impact categories, using Python scripts like the one shown in Figure 4. The parameter creation logic shown in Figure 4 is intentionally crafted as a flexible and reusable Python routine. It accepts parameter names and target categories as external inputs (IN[0] and IN[1]) instead of embedding them in the code. This approach enables the same script to be reused systematically for all indicator clusters that require new BIM parameters, simply by changing the input list of parameter names and their corresponding categories

(such as "Materials" for CAM sub-criteria, "Walls" for LCA impact categories and LEED MRc2 output).

Regarding the LEED MRc2 score indicator, a dedicated "Python" node assigns points based on the GWP of the proposed stratigraphy alternative compared to the baseline (Figure 6). The GWP is calculated via Tally and imported into Dynamo, as described. The script first computes the percentage GWP reduction relative to the baseline using Equation (3). This percentage is then matched against threshold ranges that follow the LEED v5 BD+C: NC MRc2 credit. If the reduction is less than 10%, the project is deemed non-compliant with no points awarded. For higher reductions, points increase incrementally, from 3 points for 10–20% reductions to a maximum of 6 points for reductions of 40% or more. The node outputs the reduction percentage, compliance result and LEED points, which are used to automatically update the MRc2 LEED Point parameter in Table 7, through a "Python script" comparable to the one illustrated in Figure 4.

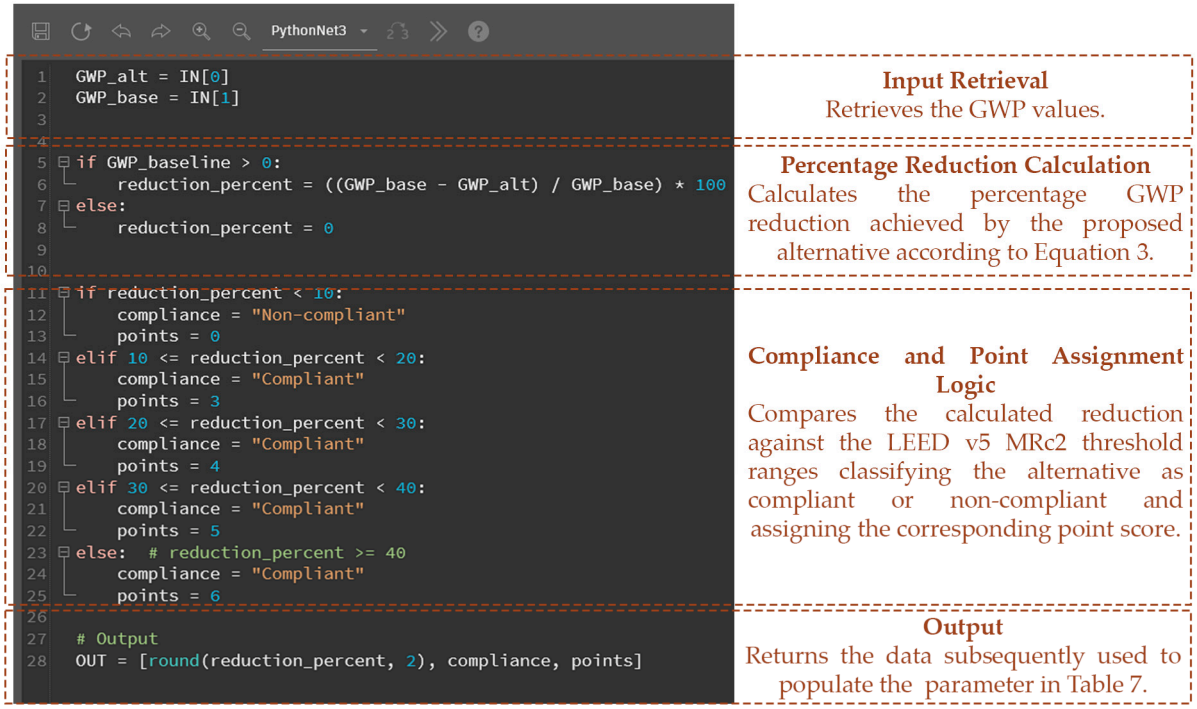



**Figure 6.** Python script for the calculation of the GWP percentage reduction and the assignment of LEED v5 MRc2 credit points. The complete script is provided as the Supplementary Materials (Script_S3_GWP_LEED_Calculation.py).

### 3.3.4. Calculation of Economic Indicator

For the calculation of the LCC indicator, a dedicated procedure is implemented, combining a Microsoft Excel spreadsheet with a Dynamo parametric script, capable of automatically calculating the construction and maintenance costs over a reference period of 60 years.

The initial step of the procedure is carried out in Microsoft Excel, where a database of materials is established, listing each material's unit price and maintenance expenses. To ensure proper functionality of the script, materials in the database are named exactly as they are in Revit. Once the database is created, a dedicated calculation sheet is set up, in which a lookup-based formula automatically retrieves the corresponding price from the database whenever a material name is entered in the reference cell:

$$IFERROR\left(VLOOKUP\left(material_name;\ 'Material\ Cost\ Database'!\ B:C;\ 2;\ FALSE\right);\ ""\right), \quad (4)$$

where material_name refers to the cell containing the material name entered for the corresponding layer, and the formula searches for a match within the material cost database, returning the associated price if found, or an empty value if no match is identified. This formula is applied to populate both the construction and maintenance cost columns for each layer of the stratigraphy. The construction costs and the maintenance costs of all layers composing the stratigraphy are then aggregated through the SUM function. For future-year maintenance costs, the Present Value (PV) of each intervention is computed, reflecting the amount needed to be invested today to yield a certain future cash flow, using the formula:

$$PV = \frac{C_t}{(1 + r)^t}, \quad (5)$$

where Ct is the maintenance cost retrieved from the database, r is the discount rate, fixed at 3%, and t is the year in which the intervention takes place (considering interventions scheduled every 15 years over a 60-year service life). The individual Present Values calculated for each reference year are then summed to obtain the total maintenance cost, which is finally added to the construction cost to obtain the total LCC of the stratigraphy.

The second step involves using Dynamo to extract stratigraphy data and export it to Excel. This process follows the same node sequence as described earlier for the wall decomposition (Section 3.3.1). The data is then exported through a series of nodes: a "File Path" node to select the Excel file, a String node to choose the worksheet, multiple "Code Block" nodes to set the starting row and column, and a "Data.ExportToExcel" node to write the data into the spreadsheet. After exporting, the Excel calculation script automatically runs to determine the construction cost, maintenance cost and total LCC for that configuration. The final part of the Dynamo script is dedicated to reintegrating the calculated total LCC value into the BIM environment through a Python script analogous to the one illustrated in Figure 4: a "Categories" node selects the target Revit category (Walls), while the Python Script node creates the numerical parameter from the provided name, making it subsequently visible under the "Data" parameter group in Revit. Upon completion of this procedure, the calculated total LCC value is made directly visible and accessible within Revit, for each of the four analysed wall stratigraphies.

### *3.4. Phase 4: Weighting and Obtaining of the Final Ranking Through VPL and TPL*

Before detailing its implementation within the BIM environment, the overall logic of the hybrid AHP/PROMETHEE ranking procedure is first presented in algorithmic form (Figure 7).

The pseudocode formalises the two main computational stages underlying the hybrid AHP/PROMETHEE procedure. In Step 1, the AHP criteria weights are derived from the Saaty pairwise comparison matrix: each column is first summed, each matrix entry is normalised by its corresponding column sum and the resulting normalised values are averaged row-wise to obtain the final weight vector, ensuring that all weights sum to one. In Step 2, the procedure performs a pairwise comparison between every pair of stratigraphy alternatives (a, b): for each criterion j, the difference between the two alternatives' indicator values is computed according to the criterion's optimisation direction (is_max), so that a positive difference always favours the better-performing alternative regardless of whether the criterion is to be maximised or minimised. This difference is then evaluated through the usual-type preference function: a preference score P of 1 is assigned if the difference is positive and 0 otherwise. Each preference score is weighted by the corresponding AHP criterion weight and accumulated into the pairwise preference index (preference_ab), which contributes to the positive flow (pos_flow) of alternative a and the negative flow (neg_flow) of alternative b. Once this procedure has been repeated across all criteria and all pairs of

alternatives, Step 3 combines the positive and negative flows of each alternative into its net outranking flow, normalised by the number of pairwise comparisons (n − 1). The four stratigraphy alternatives are then ranked in descending order of this net flow to obtain the result.

**PSEUDOCODE: HYBRID AHP/PROMETHEE RANKING**

**AHP Weight Calculation**

```
INPUT:
   alt_matrix
   saaty_matrix
   is_max

OUTPUT:
   net_flows

FOR each criterion c:
   col_sum[c] = SUM of column c across all rows of saaty_matrix
END FOR

FOR each criterion r:
   weight[r] = AVERAGE over c of ( saaty_matrix[r][c] / col_sum[c] )
END FOR
```

**PROMETHEE Pairwise Preference Calculation**

```
INITIALISE pos_flow[a] = 0, neg_flow[a] = 0  FOR each alternative a

FOR each pair of alternatives (a, b), with a ≠ b:
   preference_ab = 0
   FOR each criterion j:
      IF is_max[j] THEN
         diff = value(a, j) − value(b, j)
      ELSE
         diff = value(b, j) − value(a, j)
      END IF

      IF diff > 0 THEN
         P = 1
      ELSE
         P = 0
      END IF

      preference_ab += P * weight[j]
   END FOR

   pos_flow[a] += preference_ab
   neg_flow[b] += preference_ab
END FOR
```

**Net Flow and Final Ranking**

```
FOR each alternative a:
   net_flow[a] = ( pos_flow[a] − neg_flow[a] ) / (number_of_alternatives − 1)
END FOR

RETURN net_flow
```

**Figure 7.** Pseudocode of the hybrid AHP/PROMETHEE ranking procedure, divided into three functional blocks: AHP weight calculation from the Saaty matrix, PROMETHEE pairwise preference calculation across all criteria and alternative pairs, and the final net flow and ranking computation.

This logic is implemented within BIM through a dedicated computational pipeline that combines a customised Dynamo script for input preparation and AHP weight definition

with a Python node to execute the PROMETHEE ranking calculation, as detailed below (Figure 8).

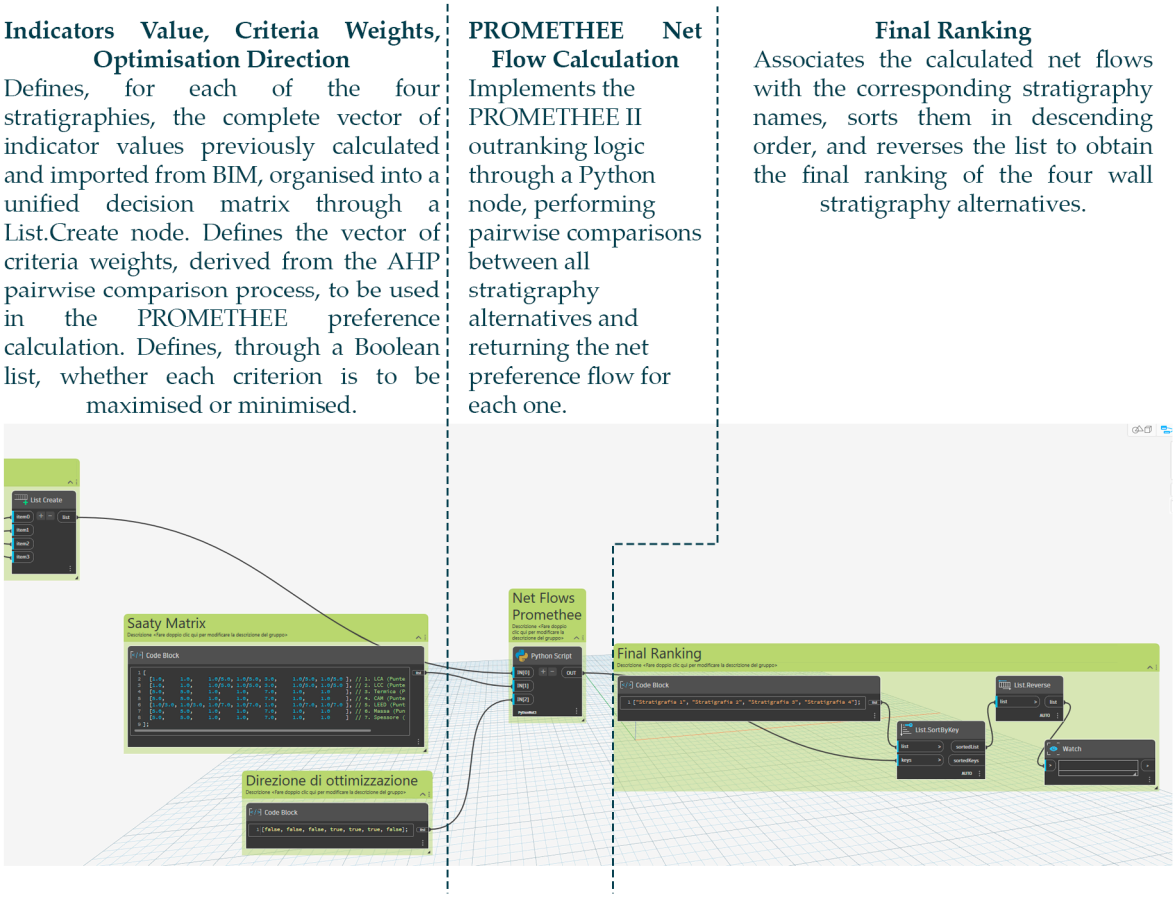



**Figure 8.** Structure of the Dynamo script implementing the hybrid AHP/PROMETHEE analysis, from input definition to the final ranking of the four wall stratigraphies.

The choice of a hybrid AHP/PROMETHEE approach is based on the complementary advantages of both methods: AHP is used to establish the relative importance of criteria via a structured pairwise comparison, offering a transparent and consistent weighting process [44], while PROMETHEE is used to rank the alternatives because it avoids the compensatory aggregation typical of purely additive methods like AHP or WSM, making it particularly effective for managing the diverse nature of the eleven indicators [45], as highlighted in Table 3.

The complete vector of indicator values previously calculated and imported from the BIM model is organised into a unified decision matrix through a "List.Create node". In parallel, the Weight group defines, through a "Code Block" node, the vector of criteria weights derived from the AHP pairwise comparison process, while the Optimisation Direction group defines, through a Boolean "Code Block", the optimisation direction associated with each criterion. The importance of the seven criteria, determined through an AHP pairwise comparison matrix based on the Saaty scale, assigns the highest importance score (7) to Periodic Thermal Transmittance, CAM Compliance, Surface Mass, and Thickness. LCA and LCC receive an intermediate score (5), while LEED is given the lowest score (3). This scoring reflects the study's focus on warm-climate envelope design: thermal transmittance and surface mass influence the envelope's dynamic thermal performance and are mandatory under D.M. 28 October 2025; thickness is a key design constraint impacting usable floor area; and CAM compliance is a mandatory regulatory requirement per Italian

procurement law (D.M. 24 November 2025). Although LCA and LCC are comprehensive, they are considered secondary to these mandatory factors, whereas LEED, as a voluntary certification, carries the least weight.

The consistency of the pairwise comparison matrix is assessed using the Consistency Ratio (CR) in accordance with the standard AHP method proposed by Saaty. The principal eigenvalue (λmax) of the matrix was obtained by solving Equation (6):

$$\mathrm{Mw} = \lambda\mathrm{max}\cdot\mathrm{w}, \tag{6}$$

where M is the comparison matrix, and w is its principal eigenvector, normalised to determine the relative criteria weights. This resulted in λmax = 7.097, close to the ideal value of 7 for perfect consistency, indicating low judgement inconsistency. The Consistency Index (CI) was then calculated by solving Equation (7):

$$\mathrm{CI} = \frac{\lambda\mathrm{max} - \mathrm{n}}{n\ -\ 1}, \tag{7}$$

where n is the number of criteria compared, and the CR was derived by solving Equation (8):

$$\mathrm{CR} = \frac{\mathrm{CI}}{RI}, \tag{8}$$

with RI being the Random Index, a reference value representing the average CI obtained from randomly generated pairwise comparison matrices of the same order, as tabulated by Saaty. This gave CR = 0.012. Since this is well below Saaty's acceptable threshold of 0.10, it confirms that the pairwise judgments are internally consistent and supports the reliability of the weighting scheme for the subsequent PROMETHEE ranking.

In terms of optimisation, LCA, LCC, thermal transmittance and thickness are minimised because lower values enhance environmental, economic, thermal, and space performance. Conversely, CAM compliance, LEED score, and surface mass are maximised, as higher values reflect better regulatory adherence, higher certification levels, and increased thermal mass, which is especially advantageous in warm climates, where greater mass helps dampen daily temperature swings and stabilise indoor temperatures.

These three inputs (indicator value, Saaty matrix and optimisation directions) feed the Net Flows PROMETHEE Python node (Figure 9), which implements the PROMETHEE II outranking logic.

Specifically, the script first acquires the decision matrix, the normalised criteria weights (ensuring their sum equals 1) and the optimisation directions as inputs. Positive and negative preference flows are then initialised for each alternative, and a pairwise comparison procedure is performed across all pairs of stratigraphy alternatives: for each pair (a, b) and each criterion j, the difference between the two alternatives is calculated according to the corresponding optimisation direction. A usual-type preference function is adopted, whereby a preference value of 1 is assigned whenever the difference favours alternative a, and 0 otherwise. This formulation is particularly suitable for the binary compliance indicators which can only take value 0 or 1. This choice is primarily driven by the presence of binary, discrete compliance-type criteria in the decision matrix, for which the usual function directly reflects the compliance/non-compliance logic without requiring additional threshold parameters. For the continuous criteria, the usual function was retained for methodological consistency across the full set of criteria. Nonetheless, criterion-specific preference functions (e.g., linear or Gaussian) could offer finer discrimination among alternatives for these indicators and are discussed as a direction for future refinement in Section 5.2. The resulting preference value is weighted by the corresponding normalised criterion weight and aggregated into the overall pairwise preference index, which contributes

to the positive flow of alternative a and the negative flow of alternative b. Once all pairwise comparisons are completed, the positive and negative flows of each alternative are averaged over the number of comparisons (n − 1) and combined into the net outranking flow (φ), calculated as the difference between the positive flow (leaving flow) and the negative flow (entering flow), consistent with the PROMETHEE II method. The resulting net flow values are returned as output to Dynamo, where they are subsequently associated with the corresponding stratigraphy names through a "Code Block" node, sorted in descending order through a "List.SortByKey" node, and reversed through a "List.Reverse" node to obtain the final ranking of the four stratigraphy alternatives, visualised through a Watch node within the Final Ranking group.

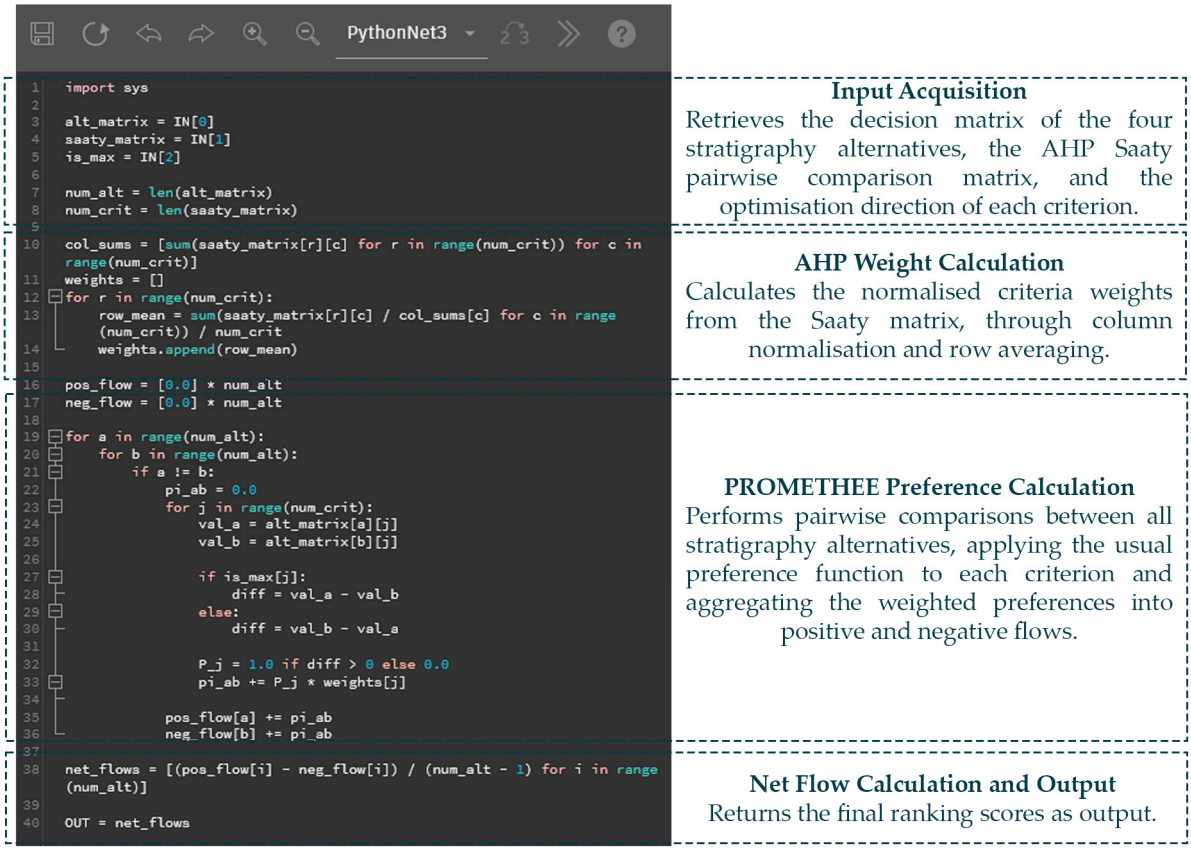



**Figure 9.** Python script implementing the hybrid AHP/PROMETHEE method, calculating criteria weights from the Saaty matrix and the final net outranking flows of the stratigraphy alternatives. The complete script is provided as the Supplementary Materials (Script_S4_AHP_PROMETHEE_Ranking.py).

## 4. Results

The proposed framework is tested on the four wall stratigraphy alternatives presented in Section 3.1, applying the complete BIM-MCDM workflow described in Section 3 to calculate the eleven thermal, environmental and economic indicators, and to obtain the final ranking of the alternatives through the hybrid AHP/PROMETHEE method.

Table 9 presents the thermo-physical performance results for the four wall stratigraphies, including thickness, periodic thermal transmittance, surface mass and thermal transmittance. All four stratigraphies exhibit values well below the 0.10 W/(m$^2$·K) regulatory limit set by D.M. 28 October 2025, indicating satisfactory damping of the envelope's dynamic thermal behaviour. Stratigraphy 4 records the lowest periodic thermal transmittance (0.003 W/m$^2$K), followed closely by Stratigraphy 1 (0.004 W/m$^2$K), while Stratigraphies 2

and 3 show higher but compliant values (0.033 and 0.048 W/m$^2$K). Surface mass analysis reveals a key distinction among the options: only Stratigraphy 1 (294 kg/m$^2$), with internal rammed earth, meets the minimum requirement of 230 kg/m$^2$. Notably, Stratigraphy 4 (150 kg/m$^2$) is below this threshold and thus non-compliant. Stratigraphies 2 (108 kg/m$^2$) and 3 (76 kg/m$^2$) fall short of the minimum surface mass, highlighting that repositioning the earth layer externally (Stratigraphy 2) or omitting it entirely (Stratigraphy 3, the lightweight frame) diminishes thermal mass capability in warm climates. Regarding thermal transmittance, all stratigraphies register low, similar values (0.152–0.206 W/m$^2$K), with Stratigraphy 4 performing best (0.152) and Stratigraphy 3 worst (0.206), though differences are small. Overall, all four stratigraphies comply with the D.M. 28 October 2025 thermophysical requirements, since the decree requires either the periodic thermal transmittance or the surface mass threshold to be satisfied. While Stratigraphy 1 is the only configuration to fully satisfy both parameters, benefiting from the combined contribution of high thermal mass and low periodic thermal transmittance provided by the rammed earth core, the remaining three stratigraphies achieve compliance exclusively through the periodic thermal transmittance requirement, as their surface mass values fall below the 230 kg/m$^2$ threshold. This distinction remains relevant for envelope performance in warm-climate contexts, where thermal mass plays an additional role in damping diurnal temperature fluctuations beyond the minimum regulatory compliance.

**Table 9.** Summary of the thermo-physical performance results obtained for the four wall stratigraphy alternatives, including thickness, periodic thermal transmittance, surface mass and thermal transmittance.

| Wall | Tickness [cm] | Periodic Thermal Transmittance [W/m$^2$K] | Surface Mass [kg/m$^2$] | Thermal Transmittance [W/m$^2$K] |
|---|---|---|---|---|
| Stratigraphy 1—Platform frame with internal rammed earth brick | 42.45 | 0.004 | 294 | 0.183 |
| Stratigraphy 2—Platform frame with external rammed earth board | 27.45 | 0.033 | 108 | 0.203 |
| Stratigraphy 3—Standard platform frame | 25.45 | 0.048 | 76 | 0.206 |
| Stratigraphy 4—X-LAM | 39.6 | 0.003 | 150 | 0.152 |

Table 10 reports the environmental sustainability results obtained for the four wall stratigraphies, in terms of GWP, percentage GWP reduction relative to the baseline, LEED MRc2 credit points and CAM compliance. Regarding the GWP indicator, Stratigraphy 1, used as the baseline, has the highest embodied carbon at 4151.21 kg$CO_2$eq, reflecting the higher material use of the internal rammed earth block. All other options show a reduction in GWP compared to this baseline, with Stratigraphy 3 (standard platform frame) achieving the greatest percentage decrease at 10.8%, followed by Stratigraphy 4 (X-LAM) at 9.9%, and Stratigraphy 2 (external rammed earth board) at 9.2%. This is because Stratigraphy 3 avoids the excavation impacts related to rammed earth extraction and processing, leading to its maximum embodied carbon savings. Accordingly, Stratigraphy 3 scores the highest on LEED MRc2 (3 points), while Stratigraphies 2 and 4 each score 2 points and the baseline Stratigraphy 1 does not receive a point score. Regarding CAM compliance, three of the four stratigraphies (1, 2 and 3) are fully compliant with the requirements outlined in the CAM decree (D.M. 24 November 2025). However, Stratigraphy 4 (X-LAM) is non-compliant because its internal plasterboard layer contains only 1% recycled material, which is below the 5% minimum threshold set by the CAM for gypsum-based partition products. It should be noted that these results are inherently dependent on the specific materials selected and on their corresponding product datasheets; a different plasterboard product, with a higher

recycled content, would potentially yield a different compliance outcome. Nonetheless, the rapid assessment enabled by the proposed tool at the design stage makes it possible to promptly detect this type of limitation directly within the BIM environment, before construction. In this respect, the tool proves particularly useful in supporting sustainability-oriented decisions from the earliest design stages, allowing designers to identify and address non-compliant material choices early in the process, rather than discovering such limitations only during later verification or procurement phases.

**Table 10.** Summary of the environmental sustainability results obtained for the four wall stratigraphy alternatives, including Global Warming Potential, percentage GWP reduction relative to the baseline, LEED MRc2 credit points and CAM compliance.

| Wall | GWP [$kgCO_2eq$] | GWP Reduction (%) | MRc2 LEED Point | CAM Compliance |
|---|---|---|---|---|
| Stratigraphy 1—Platform frame with internal rammed earth brick | 4151.21 | Baseline | Baseline | Yes |
| Stratigraphy 2—Platform frame with external rammed earth board | 3767.52 | 9.2 | 2 | Yes |
| Stratigraphy 3—Standard platform frame | 3702.11 | 10.8 | 3 | Yes |
| Stratigraphy 4—X-LAM | 3736.29 | 9.9 | 2 | No |

Overall, these findings reveal a trade-off between environmental performance linked to embodied carbon reduction and thermal mass. Stratigraphy 1 has the highest embodied carbon because of its rammed earth core, but this same feature contributes to its excellent thermo-physical performance discussed earlier. Conversely, the lightweight Stratigraphy 3, while offering the best environmental results in GWP reduction and a higher LEED score, was previously shown to meet thermo-physical requirements only through periodic thermal transmittance, due to its lack of sufficient surface mass. The findings also emphasise a broader design consideration involving the balance between thermal mass and embodied carbon in warm-climate envelope design. Solutions with higher thermal mass, like Stratigraphy 1, help stabilise indoor temperatures and can lower cooling needs but result in increased embodied carbon due to earth-based material production. In contrast, lightweight options such as Stratigraphy 3 reduce embodied carbon but may depend more on mechanical cooling in warm climates. This interaction is not fully captured by the current LCA framework (Section 3.1), which excludes operational energy impacts. This suggests that embodied-carbon reduction alone may not be sufficient to fully capture sustainable envelope performance in warm climates and that considering embodied and operational carbon together within a broader life cycle perspective could offer a more complete picture, a direction further explored in Section 5.2.

The LCC assessment for the four wall stratigraphies, calculated over the 60-year reference period, shows that maintenance costs associated with the scheduled restoration of the external render are stable across all four alternatives, with the main differences among the stratigraphies attributable to construction costs. Stratigraphy 4 (X-LAM) is the most expensive solution (409.16 €/$m^2$), explained by the extensive use of X-LAM structural panels, which are a high-cost engineered-timber component. Conversely, Stratigraphy 3 (standard platform frame) is the most economical solution (286.99 €/$m^2$), owing to the absence of any massive structural or earth-based element within the wall assembly. Stratigraphies 1 and 2, incorporating internal and external rammed earth layers respectively, are intermediate compromise solutions, with comparable total LCC values (331.39 €/$m^2$ and 333.41 €/$m^2$, respectively), reflecting the additional cost of the earth-based material without reaching the higher cost levels observed for the engineered-timber solution. Overall,

these results indicate a clear cost hierarchy among the four construction systems, with lightweight conventional platform-frame construction (Stratigraphy 3) emerging as the most cost-effective option, and massive engineered-timber construction (Stratigraphy 4, X-LAM) emerging as the most economically burdensome, while earth-based solutions (Stratigraphies 1 and 2) occupy an intermediate economic position, consistent with their intermediate thermal mass performance.

The hybrid AHP/PROMETHEE method yields the final ranking of the four wall stratigraphy alternatives, derived from the net outranking flows calculated for each configuration. Stratigraphy 2 (platform frame with external rammed earth board) ranks first, followed by Stratigraphy 1 (platform frame with internal rammed earth brick), Stratigraphy 3 (standard platform frame), and Stratigraphy 4 (X-LAM), which ranks last. This ranking shows that Stratigraphy 2 achieves a balanced performance across the weighted criteria: while not excelling in any single indicator, it offers a combination of reduced thickness and construction costs compared to Stratigraphy 1, along with a 9.2% GWP reduction and full CAM and LEED compliance. It also meets the D.M. 28 October 2025 thermo-physical standards, resulting in the best overall trade-off among key weighted criteria like thermal transmittance, thickness and CAM compliance. Stratigraphy 1 ranks second, mainly due to its superior thermo-physical properties, being the only option to meet both the periodic thermal transmittance and surface mass thresholds, though it is slightly disadvantaged by greater thickness, higher costs, and higher embodied carbon. Although Stratigraphy 3 shows the best environmental results, most notably in GWP reduction, LEED score and LCC, it ranks third because of its comparatively lower surface mass and thermal transmittance within the highly weighted thermal criteria. Finally, Stratigraphy 4 (X-LAM) ranks last mainly due to CAM non-compliance and the highest LCC, which are not fully offset by its better thermal transmittance and reduced periodic thermal transmittance.

Alongside the standard MCDM analysis, a what-if scenario is examined where the LEED MRc2 score is removed from the multi-criteria assessment. This approach is driven by the fact that the LEED MRc2 credit originates from the GWP indicator, which is also explicitly included in the LCA impact categories. Including both may lead to double-counting of the GWP information, which could skew the overall environmental ranking. This scenario aims to evaluate how much this potential double-counting impacts the final ranking of the stratigraphy options. Under this alternative weighting configuration, the resulting ranking is as follows: Stratigraphy 1 (platform frame with internal rammed earth brick) is ranked first, followed by Stratigraphy 2 (platform frame with external rammed earth board), Stratigraphy 4 (X-LAM), and, finally, Stratigraphy 3 (standard platform frame), which now occupies the last position. This outcome shows a shift from the previous scenario, where Stratigraphy 2 was first and Stratigraphy 3 was third. After removing the LEED indicator, Stratigraphy 1 becomes the top choice because of its superior thermo-physical performance, the only setup meeting both the periodic thermal transmittance and surface mass thresholds. Conversely, Stratigraphy 3, which had the highest LEED score (3 points) for its GWP reduction, drops to last place once this credit is excluded. Its weaker thermo-physical performance, which only met standards via the periodic thermal transmittance pathway due to limited surface mass, is no longer balanced by its environmental benefits. Stratigraphy 4 (X-LAM) rises from fourth to third as the removal of the LEED score diminishes an indicator that it did not score well on, letting its strong thermal transmittance stand out more in the simplified criteria. Stratigraphy 2 remains consistently in the top tier across both scenarios, demonstrating its balanced performance across the remaining criteria.

Overall, this what-if analysis confirms that the LEED MRc2 indicator exerts a non-negligible influence on the final ranking, given its methodological dependence on the GWP value already accounted for within the LCA cluster; its inclusion tends to reward

alternatives achieving the highest GWP reduction (Stratigraphy 3), while its exclusion shifts the ranking in favour of alternatives with superior thermo-physical performance (Stratigraphy 1). This result highlights the importance of carefully considering potential indicator redundancy when defining the criteria set for MCDM-based sustainability assessments and confirms the value of the proposed digitalised and iterative framework, which enables such alternative scenarios to be rapidly explored and compared, supporting a more transparent and informed interpretation of the final design recommendation.

## 5. Discussion

### *5.1. Positioning Within the Existing Literature*

The proposed framework addresses the four gaps identified in the critical analysis of previous studies presented in Section 2, namely the absence of a standardised MCDM method, the lack of holistic and consistent indicator sets, the persistence of manual or externally implemented calculation and weighting procedures, and the uneven practical validation through case studies.

Regarding the methodological gap, the reviewed literature shows variability in the MCDM techniques used, ranging from AHP, ANP, and WSM to WASPAS-G, Delphi-BWM, PROMETHEE, and TOPSIS in their fuzzy variants, without a common reference point across studies. Instead of relying on a single method, this study employs a hybrid AHP/PROMETHEE approach, intentionally combining the transparent, structured pairwise-comparison weighting of AHP with the non-compensatory outranking logic of PROMETHEE II. The latter is particularly suitable for the diverse set of eleven indicators, which include continuous quantitative variables, discrete scores and binary compliance outcomes. This hybrid method addresses the point raised in Section 2 that the choice of technique should be tailored to the specific decision-making context rather than dependent on a universally optimal method.

About the gap related to indicators, previous research often focused on only one sustainability dimension, such as purely environmental [38,40] or solely economic/process-related criteria [35,37,40]. This study addresses this limitation by systematically combining eleven indicators across three key areas, namely thermo-physical, environmental and economic. It explicitly includes regulatory compliance (D.M. 28 October 2025, CAM), voluntary certification (LEED MRc2), six LCA impact categories, and life cycle costing within a unified, comprehensive framework. Beyond the "what-if" scenario in Section 4, which examined how the LEED MRc2 indicator affected the final ranking, this study did not perform a comprehensive sensitivity analysis of all major criterion weights. The framework's automated system enables quick re-evaluation with different weightings by rerunning the Dynamo–Python workflow, but a parametric analysis of the entire weight space was beyond the scope of this study. Such an analysis is planned for future research to enhance confidence in the stability of the reported ranking.

Regarding the automation gap, most prior studies relied on manual calculations and weighting methods [31,34–37] or delegated MCDM logic to external, non-BIM tools like MATLAB [38–40]. This study advances the field by integrating the entire computational process within a unified Revit–Dynamo–Python setup. Manual effort is only required for initial data acquisition (e.g., product datasheets, CAM certifications), while all other steps are automated. This approach, detailed in Tables 4–8, directly addresses scalability concerns discussed in Section 2, showing how manual procedures become less feasible as the number of indicators increases. Notably, even studies using similar technology stacks as this work are limited in this regard: Parisi et al. [32], although using Revit, Dynamo and Tally for indicator calculation, relied on a single AHP method with compensatory aggregation and a narrower set of indicators. Similarly, Namaki et al. [38] combined BIM

and AHP for environmental assessment but handled weighting and ranking manually, outside the BIM environment. In contrast, the current framework automates indicator calculation and incorporates the entire weighting and non-compensatory ranking logic (AHP/PROMETHEE) directly within the BIM–Dynamo–Python pipeline, addressing this remaining automation gap.

Concerning the validation gap, many earlier studies were purely theoretical or conceptual, lacking case studies [34,36,37]. This research validates the framework through four real, constructionally representative wall stratigraphies, from massive rammed-earth systems to lightweight platform-frame and engineered-timber (X-LAM) options. This showcases the framework's applicability to practical design choices in warm climates. Furthermore, a what-if scenario assesses how potential indicator redundancy, such as LEED-LCA double-counting, might influence the final ranking, underscoring methodological robustness.

### *5.2. Limitations and Future Research*

Some limitations of the present study are acknowledged, each suggesting a direction for future research.

The framework has been validated on four wall stratigraphies, all applied to a single envelope type (external wall) and a Mediterranean warm climate context. Future research could expand this validation to include other stratigraphy options, additional envelope components (such as roof and ground floor assemblies), and various climatic zones to test the consistency of relative performance across different boundary conditions. It is important to highlight that the computational tool is not restricted to the four stratigraphies analysed in this study. Its parametric, BIM-native architecture is independent of specific materials or systems and can easily be adapted to a wider variety of sustainable envelope systems and materials, with customisation limited to the material database outlined in Section 3.2. Nevertheless, the rankings and trade-off results, including the identification of the top-performing stratigraphy, are specific to this case study within a Mediterranean warm-climate setting. Applying these findings to other material types or climates will require further validation to ensure their broader applicability.

The CAM compliance results are also shown to depend on the specific materials chosen and their product datasheets, as demonstrated by the non-compliance found for Stratigraphy 4. Additionally, the LCA background database (GaBi, via Tally) is primarily representative of US-average material production conditions. Future work could incorporate region-specific EPD data to further refine the geographical accuracy of environmental results in the Mediterranean context and enable automatic retrieval of continuously updated certified material data. Additionally, although Section 4's what-if scenario examined the overlap between the GWP and LEED MRc2 indicators, a comprehensive correlation analysis across all eleven indicators was not conducted in this study. Such an analysis would benefit from a larger case-study set beyond the current four stratigraphies to enhance statistical robustness, and is suggested as a future research direction.

Additionally, the AHP criteria weights are set by the research team based on regulatory priorities and warm climate design needs. Although the framework permits adjusting these weights and rerunning the analysis quickly, as shown in the what-if scenario in Section 4, future research could incorporate structured expert elicitation methods (such as Delphi) to develop more validated weighting schemes or explore group decision-making extensions of the AHP/PROMETHEE approach. This sensitivity to weighting configuration, as shown by the what-if scenario in Section 4, has a clear practical implication: the resulting ranking should be seen as a transparent, customizable decision-support tool that reflects the specific priorities embedded in the current weighting scheme. It should not be regarded as an

absolute or definitive measure of sustainability performance. Practitioners using this framework across different projects or contexts are advised to critically review and, if needed, modify the criteria weights to align with their regulatory environment and design goals. The framework's automated architecture makes it easy to adjust these weights quickly without altering the core computational logic.

Moreover, the PROMETHEE implementation applies a single usual-type preference function uniformly across both binary/discrete and continuous criteria. While well suited to the binary compliance indicators in the criteria set, this choice does not exploit the finer discrimination that criterion-specific preference functions (e.g., linear or Gaussian) could offer for the continuous criteria and may therefore influence the resulting ranking, particularly among alternatives with small numerical differences on these criteria. Future developments could implement criterion-specific preference functions to test the sensitivity of the ranking to this methodological choice. Similarly, the choice of Stratigraphy 1 as the baseline for the LEED MRc2 credit calculation, while justified on constructive grounds (Section 3.1), was not systematically tested against alternative baseline configurations. Since the LEED MRc2 score and the associated GWP percentage reduction are both computed relative to this baseline (Section 3.1), an alternative baseline stratigraphy could influence the final PROMETHEE ranking. Future work should therefore assess how sensitive the GWP percentage reduction, the LEED score and, ultimately, the final ranking of alternatives are to this baseline choice.

The economic assessment relies on a fixed discount rate and a specific national cost database, which are context-dependent. Future research could extend the LCC module to support variable-discount-rate scenarios and regionally calibrated databases, enabling comparisons across different market contexts. Similarly, the current LCA system boundary excludes operational energy impacts, so the observed trade-off between thermal mass and embodied carbon cannot be fully evaluated in terms of its net effect on whole-life carbon performance. Future work could extend the framework to jointly account for embodied and operational carbon within a unified life cycle perspective.

In addition, the current workflow depends on a specific software ecosystem (Autodesk Revit, Dynamo, and Tally). Additionally, the periodic thermal transmittance values obtained through the custom Excel-Dynamo calculation procedure (Section 3.3.2) have not been benchmarked against an independent thermal simulation tool, such as EnergyPlus or THERM. Future work could explore transferring this computational logic to other BIM platforms, LCA and energy-related tools, broadening the framework's applicability across different professional software environments.

## 6. Conclusions

The increasing environmental footprint of construction demands digital tools to aid sustainability-focused decisions early in design. This study introduces and tests a Decision Support System (DSS) that merges BIM, VPL and TPL to determine the best wall stratigraphy for the building envelope. It features four automated phases, using Autodesk Revit, Dynamo and Python for integration.

The proposed framework systematically evaluates eleven indicators related to thermal performance, environmental impact and economics, covering regulatory compliance (D.M. 28 October 2025, CAM), voluntary certification (LEED MRc2), six LCA impact categories, and life cycle costing. It then integrates these results into a hybrid AHP/PROMETHEE multi-criteria analysis within the BIM environment. Validated on four sustainable wall stratigraphies for warm climates, ranging from massive rammed-earth to lightweight platform-frame and engineered timber (X-LAM), the results show that, under the baseline weighting configuration and baseline stratigraphy adopted in this study, a hybrid approach

combining thinner rammed earth with a lightweight platform-frame structure offers the best overall balance across performance metrics. As discussed in Section 5.2, the stability of this result under alternative weight configurations or baseline choices was not systematically tested and remains a priority direction for future research. In contrast, fully massive and fully lightweight options are less optimal due to higher costs, embodied carbon, or inadequate thermal mass. An additional scenario demonstrates the framework's ability to quickly test different weighting configurations, emphasising its sensitivity to indicator redundancy and underscoring the benefits of a digital, iterative sustainability assessment.

Although the framework is applied here to a specific set of stratigraphies, its computational structure is independent of these configurations: extending the analysis to other stratigraphic solutions only requires updating the BIM models, with no need to redevelop the underlying calculation and ranking procedures.

The main contribution of this study lies in demonstrating how the systematic integration of BIM, VPL and TPL can overcome the automation, comprehensiveness and validation limitations identified in previous research, resulting in a fully automated, end-to-end BIM-MCDM workflow that provides designers with immediate, dynamically updatable results directly within the BIM environment. Despite certain limitations related to the specific case study scope, material data dependency, weighting subjectivity and software ecosystem, discussed in Section 5.2, the proposed framework represents a replicable and scalable pathway for integrating digital sustainability assessment into early-stage design practice.

Future studies should aim to validate the approach across more envelope types and climate conditions, integrate comprehensive EPD databases, include expert-based weighting processes, and test the adaptability of the computational logic to other BIM and LCA software platforms.

From a practical standpoint, the proposed framework is intended for use at early design stages, such as schematic or preliminary design, when envelope options are still open for comparison and key decisions significantly impact the building's sustainability. Its use in professional practice requires a BIM model with the material and layer info from Section 3.2 and the shared parameter structure from Section 3.3. Once these are in place, designers can quickly generate a ranked comparison of envelope options in minutes rather than days, enabling rapid iteration. This supports early-stage discussions on sustainability with clients and teams, rather than reserving these for later detailed design or certification phases. The what-if analysis feature also enables practitioners to transparently test different weighting priorities during workshops, clarifying and negotiating the trade-offs that influence the final ranking among stakeholders.

Overall, this research advances the shift toward data-driven and digitally supported sustainable construction, providing a practical tool that allows for transparent consideration of thermal, environmental and economic factors in selecting sustainable building envelopes.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18168608/s1, Script S1: Python script for the automated extraction of specific heat capacity from Revit materials (Figure 3—Script_S1_Specific_Heat_Extraction.py). Script S2: Python script for the automated creation of shared parameters within the Revit project (Figure 4—Script_S2_Shared_Parameter_Creation.py). Script S3: Python script for the calculation of the GWP percentage reduction and assignment of LEED v5 MRc2 credit points (Figure 6—Script_S3_GWP_LEED_Calculation.py). Script S4: Python script implementing the hybrid AHP/PROMETHEE method for criteria weighting and final ranking (Figure 9—Script_S4_AHP_PROMETHEE_Ranking.py).

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## References

1. Pristerà, G.; Ramon, D.; Alaux, N.; Wierzgala, P.; Sala, S.; Passer, A.; Allacker, K. Assessing the Environmental Impact of European Residential Buildings in 2020: A Comparison of Two Building Stock Models for Policy Support. *Int. J. Life Cycle Assess.* **2026**, *31*, 120. [CrossRef]
2. Arab, B.; Abdel Raouf, M.; Rahal, A.; Mostafa, M.; AbouZeid, M.N. Life Cycle Assessment for Construction Materials of an Industrial Building Using Web-Based Software "OneClick LCA". *Discov. Sustain.* **2025**, *6*, 615. [CrossRef]
3. Feng, H.; Zhao, J.; Hollberg, A.; Habert, G. Where to Focus? Developing a LCA Impact Category Selection Tool for Manufacturers of Building Materials. *J. Clean. Prod.* **2023**, *405*, 136936. [CrossRef]
4. Martín-Civantos, M.; Carrasco-Aguilar, C.; Hormazabal, J.P.; Navarro, S. Technical Criteria in Construction Materials Education in Spain: A Curriculum Analysis of Sustainability, Regulation, and Material Use. *Buildings* **2026**, *16*, 2166. [CrossRef]
5. United Nations Transforming Our World: The 2030 Agenda for Sustainable Development. Available online: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication (accessed on 22 January 2025).
6. All Analysis–Analysis-IEA. Available online: https://www.iea.org/analysis (accessed on 29 July 2026).
7. D'Agostino, D.; Minelli, F.; Minichiello, F.; Russo, N. The Impact of the New EPBD "Green Houses" in the Italian Building Context: Technical-Economic Analysis on Improving the Energy Class of Existing Buildings. *E3S Web Conf.* **2024**, *523*, 04005. [CrossRef]
8. European Commission. *The European Green Deal*; European Commission: Brussels, Belgium, 2019.
9. Ministero dell'Ambiente e della Sicurezza Energetica. *Decreto 28 Ottobre 2025*; Ministero dell'Ambiente e della Sicurezza Energetica: Roma, Italy, 2025.
10. *ISO 14040:2006(En)*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006. Available online: https://www.iso.org/obp/ui/en/#iso:std:iso:14040:ed-2:v1:en (accessed on 11 March 2026).
11. Van Gulck, L.; Wastiels, L.; Steeman, M. How to Evaluate Circularity through an LCA Study Based on the Standards EN 15804 and EN 15978. *Int. J. Life Cycle Assess.* **2022**, *27*, 1249–1266. [CrossRef]
12. Seseña, M.S.O.; Ríos, J.A.T.; Ortega, G.S.; Brockmann, T.; Conde, M. UNE-EN 15804:2012+A2: Analysis of the Stabilisation of Environmental Impacts in Environmental Product Declarations. Case of Mass Concrete. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Prague, Czechia, 16–19 September 2025; Volume 1546.
13. U.S. Green Building Council. LEED v5. Available online: https://www.usgbc.org/leed/v5 (accessed on 29 July 2026).
14. European Commission. *(First) CPR Working Plan for 2026–2029*; European Commission: Brussels, Belgium, 2025.
15. European Commission. EU Taxonomy for Sustainable Activities—Finance. Available online: https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en (accessed on 29 July 2026).
16. Ministry of the Environment and Energy Security (MASE). *National Action Plan on Green Public Procurement (PANGPP)—Minimum Environmental Criteria for the Award of Design and Works Supervision Services for Building Interventions and Civil Engineering Works, and for the Execution of Works, Including Construction, Renovation, Maintenance, and Upgrading Interventions*; Ministry of the Environment and Energy Security (MASE): Rome, Italy, 2025.
17. Bassolino, E. The DNSH Principle for the Construction Sustainability of PINQuA Programme Works in Naples and Caserta. *TECHNE-J. Technol. Archit. Environ.* **2024**, *27*, 197–206. [CrossRef]
18. Di Maria, A.; Eyckmans, J.; Van Acker, K. Downcycling versus Recycling of Construction and Demolition Waste: Combining LCA and LCC to Support Sustainable Policy Making. *Waste Manag.* **2018**, *75*, 3–21. [CrossRef] [PubMed]
19. Uygunolu, T.; Keçebasç, A. LCC Analysis for Energy-Saving in Residential Buildings with Different Types of Construction Masonry Blocks. *Energy Build.* **2011**, *43*, 2077–2085. [CrossRef]

20. *ISO 15686-5:2017*; Buildings and Constructed Assets—Service Life Planning—Part 5: Life-Cycle Costing. ISO: Geneva, Switzerland, 2017. Available online: https://www.iso.org/standard/61148.html (accessed on 29 July 2026).
21. *EN 16627:2015*; Economic Performance Assessment of Buildings Using LCC. CEN: Brussels, Belgium, 2015. Available online: https://standards.iteh.ai/catalog/standards/cen/873a2524-808c-4843-b1db-35520c48146a/en-16627-2015?srsltid=AfmBOooe7uTuJxbwM0pWn0WWDZG4aqnTwbcHLug7wu_DIqt8WixXtnOl (accessed on 29 July 2026).
22. Al-Obaidy, M.; Courard, L.; Attia, S. A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles. *Sustainability* **2022**, *14*, 3370. [CrossRef]
23. Trofimenko, I.; Chen, Y.; Müller, A.K.; Liebau, U.; Flore, A. Real-Time LCA/LCC Integration: A Framework of Agile Sustainability and Cost Management. *Sustainability* **2025**, *17*, 9433. [CrossRef]
24. Fernández-Mora, V.; Navarro, I.J.; Yepes, V. Extending Building Lifespan: Integrating BIM and MCDM for Strategic Rehabilitation. *J. Inf. Technol. Constr.* **2026**, *31*, 398–419. [CrossRef]
25. Tsai, W.H.; Lin, S.J.; Lee, Y.F.; Chang, Y.C.; Hsu, J.L. Construction Method Selection for Green Building Projects to Improve Environmental Sustainability by Using an MCDM Approach. *J. Environ. Plan. Manag.* **2013**, *56*, 1487–1510. [CrossRef]
26. Si, J.; Marjanovic-Halburd, L.; Nasiri, F.; Bell, S. Assessment of Building-Integrated Green Technologies: A Review and Case Study on Applications of Multi-Criteria Decision Making (MCDM) Method. *Sustain. Cities Soc.* **2016**, *27*, 106–115. [CrossRef]
27. Yang, M.; Moon, J.; Jeong, J.; Sin, S.; Kim, J. A Novel Embedding Model Based on a Transition System for Building Industry-Collaborative Digital Twin. *Appl. Sci.* **2022**, *12*, 553. [CrossRef]
28. Jebelli, S.T.; Behnam, B. BIM-Driven Optimization of Life Cycle Cost in Seismic Design of Urban Buildings. *Innov. Infrastruct. Solut.* **2024**, *9*, 474. [CrossRef]
29. Ferreira Alves, G.; Gripp, A.K.; Munaro, M.R.; Tavares, S.F.; Bragança, L. Application of Materials Passport to the Wood Frame Construction System Using Revit and Dynamo. *Buildings* **2025**, *15*, 4323. [CrossRef]
30. Dubljević, S.; Tepavčević, B.; Stefanović, A.; Anđelković, A.S. BIM to BREEAM: A Workflow for Automated Daylighting Assessment of Existing Buildings. *Energy Build.* **2024**, *312*, 114208. [CrossRef]
31. Bernardo, G.; Palmero Iglesias, L. A Multi-Criteria Decision-Support Framework for Heritage Materials. *Appl. Sci.* **2026**, *16*, 4564. [CrossRef]
32. Parisi, G.; Cascone, S.; Gugliuzzo, A.; Caponetto, R. Automated BIM-Driven Multi-Criteria Assessment of External Wall Design: Evaluating Thermal Insulation Alternatives. *Sustainability* **2026**, *18*, 3585. [CrossRef]
33. Cascone, S.; Anastasi, V.; Caponetto, R. Performance Optimization of Building Envelope Through BIM and Multi-Criteria Analysis. *Sustainability* **2025**, *17*, 5294. [CrossRef]
34. Haruna, A.; Shafiq, N.; Montasir, O.A. Building Information Modelling Application for Developing Sustainable Building (Multi Criteria Decision Making Approach). *Ain Shams Eng. J.* **2021**, *12*, 293–302. [CrossRef]
35. Pavlovskis, M.; Antucheviciene, J.; Migilinskas, D. Assessment of Buildings Redevelopment Possibilities Using MCDM and BIM Techniques. *Procedia Eng.* **2017**, *172*, 846–850. [CrossRef]
36. Li, C.; Petzold, F. Integrating Digital Design and Additive Manufacturing Through BIM-Based Digital Support—A Decision Support System Using Semantic Web and Multi-Criteria Decision Making. *Projections* **2021**, *1*, 263–270. [CrossRef]
37. Naji, A.J.; Jabbar, A.H.M.; Abu Mahadi, M.I. Justifying Integration of BIM Technique in Sustainability Practices in Building's Construction: A Hybrid Delphi-BWM Analysis. *J. Eng. Proj. Prod. Manag.* **2025**, *16*, 2025–2037. [CrossRef]
38. Namaki, P.; Vegesna, B.S.; Bigdellou, S.; Chen, R.; Chen, Q. An Integrated Building Information Modeling and Life-Cycle Assessment Approach to Facilitate Design Decisions on Sustainable Building Projects in Canada. *Sustainability* **2024**, *16*, 4718. [CrossRef]
39. Chen, L.; Pan, W. BIM-Aided Variable Fuzzy Multi-Criteria Decision Making of Low-Carbon Building Measures Selection. *Sustain. Cities Soc.* **2016**, *27*, 222–232. [CrossRef]
40. Fazeli, A.; Jalaei, F.; Khanzadi, M.; Banihashemi, S. BIM-Integrated TOPSIS-Fuzzy Framework to Optimize Selection of Sustainable Building Components. *Int. J. Constr. Manag.* **2022**, *22*, 1240–1259. [CrossRef]
41. *UNI EN ISO 13786:2018*; Thermal Performance of Building Components—Dynamic Thermal Characteristics—Calculation Methods. UNI (Ente Italiano Di Normazione): Milan, Italy, 2018. Available online: https://store.uni.com/uni-en-iso-13786-2018 (accessed on 1 March 2026).
42. U.S. Green Building Council. Reduce Embodied Carbon. Available online: https://www.usgbc.org/credits/new-construction/v5/mrc2 (accessed on 29 July 2026).
43. European Parliament. Council of the European Union Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the Establishment of a Framework to Facilitate Sustainable Investment, and Amending Regulation EU 2019/2088. In *Official Journal of the European Union*; European Union: Brussels, Belgium, 2020.

44. Ulas Sariaydin, E. AHP Multi-Criteria Decision-Making Model for Selecting an Energy Renovation Scenario for a Historic Building. *Int. J. Archit. Herit.* **2026**, *20*, 585–603. [CrossRef]
45. Le Teno, J.F.; Mareschal, B. An Interval Version of PROMETHEE for the Comparison of Building Products' Design with Ill-Defined Data on Environmental Quality. *Eur. J. Oper. Res.* **1998**, *109*, 522–529. [CrossRef]

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