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Luís Bragança · Katerina Tsikaloudaki · Christina Giarma · Ricardo Mateus · Karolos Kontoleon · Rand Askar · Adriana Salles · Camila Cervantes *Editors*

ReShaping the Built Environment through Sustainability and Circularity

Proceedings of ReSBE 2026 International Conference - Volume 1

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Preface

As Organisers of ReSBE 2026, we are honoured to present the Proceedings of the International Conference *ReShaping the Built Environment through Sustainability and Circularity*, held in Thessaloniki, Greece, from the 20th to the 23rd of October 2026.

Published in Open Access by Springer, these Proceedings reflect our commitment to making research and practical innovation at the intersection of sustainability, circularity, and the built environment widely available. By ensuring that the contributions can be consulted, cited and applied without restrictions, we hope to support informed decisions and accelerate positive change in the built environment and in society as a whole.

Society and governments require a more efficient, resilient, and regenerative built environment. Buildings and infrastructure shape patterns of resource use, energy demand, carbon emissions, social well-being, and economic development. In this context, the Circular Economy offers a vital framework for decoupling value creation from the consumption of finite resources by extending the service life of products and materials, enabling reuse and recovery, and promoting the valorisation of by-products and waste. Construction and the built environment have therefore become priority areas for policy, research, and professional practice, including within the European Commission's Circular Economy Action Plan. In parallel, the implementation of sustainability principles into the various scales of the built environment remains a primary goal of numerous policies and scientific efforts worldwide. ReSBE 2026 responds to this complex agenda by moving beyond incremental improvement and by advancing transformative approaches that drive systemic change across the design, construction, operation, and renewal of the built environment.

The conference was organised by the Laboratory of Building Construction and Building Physics of the School of Civil Engineering, Aristotle University of Thessaloniki, and the Department of Civil Engineering of the University of Minho, in collaboration with the COST Action CA21103 "Implementation of Circular Economy in the Built Environment – CircularB", with the support of the International Initiative for a Sustainable Built Environment (iiSBE).

ReSBE 2026 also marked an important moment in the journey of COST Action CircularB. Alongside presenting cutting-edge research, the conference provided an opportunity to showcase the Action's achievements, disseminate its results, and celebrate the collective efforts of its international network in advancing circularity in the built environment. More importantly, it created a platform for engaging the wider scientific, professional, and policy communities, fostering new collaborations and extending the impact of CircularB beyond the lifetime of the Action.

Within the ReSBE 2026 programme, the 1SBE event "Sustainability in the Built Environment Supported by Circular Strategies: Theory Meets Practice" further strengthened the conference's international scope. As part of the SBE Conference Series, this event created a forum for dialogue among policymakers, industry representatives, social

partners, and academics, thereby linking scientific knowledge with implementation challenges and opportunities.

ReSBE 2026 was devoted to presenting recent scientific advances, showcasing practical applications that bridge academia and industry, and discussing key issues concerning the contribution of sustainability and circularity to the modern and future built environment, its construction, and its infrastructure. A principal goal of the conference was to foster the exchange of ideas, methods, and evidence in ways that inspired innovative research paths and advanced new collaborative endeavours across disciplines, geographies, and sectors.

The conference received 541 abstracts from 1368 authors across 71 countries. Following a rigorous peer-review process, 335 full scientific papers were accepted for publication and organised into twelve thematic sections:

1. *Circular Design and Construction:* design for adaptability, reuse, and disassembly; material passports; modularity and standardisation.
2. *Sustainable Buildings, Infrastructures and Cities:* sustainability assessment frameworks, sustainable design, construction, operation and management; synergies across scales.
3. *Lifecycle Assessment, Metrics and Monitoring:* whole-life carbon, embodied energy, circularity indicators, benchmarking frameworks, multi-criteria decision-support methods, and AI/IoT-enabled lifecycle monitoring.
4. *Digitalisation and Automation:* BIM-based approaches, digital twins, digital passports, AI-powered tools, and decision-support systems.
5. *Climate Adaptation and Resilience:* climate-responsive design, resilient infrastructure, and nature-based solutions.
6. *Energy and Performance:* net-zero energy, carbon-neutral buildings, renewable energy integration, and smart grids.
7. *Materials and Innovation:* bio-based and regenerative materials, advanced composites, and secondary raw materials through industrial symbiosis.
8. *Urban and Regional Perspectives:* circular cities, heritage regeneration, and urban mining.
9. *Financing and Market Transformation:* circular business models, green financing, and innovative procurement strategies.
10. *Policy and Governance:* regulatory frameworks, certification systems, and leadership for circularity.
11. *Stakeholders and Collaboration Models:* roles, interactions, and governance mechanisms for systemic change.
12. *Societal and Educational Dimensions:* awareness, equity, skills, and capacity-building for sustainable transitions.

The contributions in these proceedings offer readers a broad and timely overview of the concepts, tools, technologies, policies, and case studies that are shaping the transition towards a sustainable and circular built environment. They address questions of direct relevance to researchers, designers, engineers, architects, policymakers, educators, and industry stakeholders, from whole-life performance and digitalisation to financing models, governance frameworks, stakeholder collaboration, and capacity-building.

Taken together, these contributions demonstrate that innovation, circularity, and sustainability are deeply interconnected. They also show that progress depends not only on technical solutions, but also on new forms of cooperation, new metrics for value and performance, and a shared willingness to rethink established practices. In light of this, the present Open Access publication aims to be a collection of high-quality research and serve as a catalyst for further inquiry, dialogue, collaboration and action.

We extend our deepest gratitude to all authors, the members of the Scientific Committee, the reviewers whose careful work upheld the excellence of the selected articles, and our publishing partners for their invaluable support. May these Proceedings inspire and facilitate the ongoing effort to engineer a sustainable, circular, and regenerative built environment for all.

The Organising Committee,

Luís Bragança
Katerina Tsikaloudaki
Christina Giarma
Ricardo Mateus
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Adriana Salles
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Whole Life Carbon Assessment as a Tool for Urban Climate Action

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Abstract. The mitigation of building-related greenhouse gas emissions (CO_2eq) is now recognised as a prerequisite for achieving long-term climate objectives. Several European countries and local communities are taking action to implement the Whole Life Carbon (WLC) vision and make it practical, enabling the assessment of building life-cycle emissions. The paper presents a simplified, standardised methodology for assessing WLC in building projects, developed as part of scientific research carried out for an Italian Municipality. The proposed framework aims to support the systematic accounting and reporting of CO_2eq emissions associated with new construction and renovations. The methodology is grounded in the Life Cycle Assessment standard and consistent with European standards and policy measures, including EN 15978, EN 15804, the Level(s) framework, and the Energy Performance of Buildings Directive recast (EPBD, EU 2024/1275). It focuses on selected life cycle modules: production (A1–A3), construction (A4–A5), use (B4, B6), and end-of-life (C2–C4). A twofold application is defined, encompassing a WLC evaluation at both the early design phase and the as-built report, utilising different data and quality levels (e.g., material generic data vs. product-specific data).

The paper outlines a simplified WLC framework to enhance comparability and decision-making in municipal contexts. Since the framework has not yet been validated through real case studies, the contribution describes the methodology underlying the simplified WLC assessment. This methodology represents the basis for a subsequent research phase focused on the application and validation of the framework in real case studies.

Keywords: Whole Life Carbon · Embodied Carbon · Operational Carbon · Life Cycle Assessment · Building standard

1 Introduction

The decarbonisation of the built environment is widely recognised as a critical component of global climate mitigation strategies. Buildings account for a substantial share of global greenhouse gas emissions, due to both operational energy use and embodied emissions associated with construction materials and processes [1, 2].

Historically, since Regulation 2018/1999, policies aimed at reducing the environmental impact of buildings have primarily focused on operational energy use [3]. However,

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improvements in building energy efficiency are progressively increasing the relative importance of embodied emissions associated with materials, construction activities and end-of-life processes. Consequently, the concept of Whole Life Carbon (WLC) has emerged as a comprehensive framework for assessing the total greenhouse gas emissions associated with buildings throughout their life cycles [4, 5].

WLC assessment builds upon the methodological principles of Life Cycle Assessment (LCA) and is increasingly supported by international standards and European policy initiatives. In particular, the European standards UNI EN 15978 and UNI EN 15804 provide a consistent methodological basis for calculating the environmental impacts of buildings and construction products [6, 7]. From the policy standpoint, the Level(s) framework and the fourth recent recast of the Energy Performance of Buildings Directive (EPBD IV) require assessing the Global Warming Potential (GWP) across the entire building life cycle, accounting for CO_2-equivalent (CO2eq) emissions [8, 9].

Finally, some national and local initiatives have been introduced. In Italy, the Municipality of Milan adopted the "Piano Aria e Clima" (Air and Climate Plan) in 2021 to reach climate neutrality by 2050 [10]. At the same time, the recently introduced national standard UNI 11973:2025 highlights the relevance of decarbonising buildings. It sets out guidelines and procedures for WLC accounting [11].

In this context, there is a growing need for shared methodologies that enable designers to quantify carbon emissions effectively. This paper presents the development of "Operational Instructions" for a **simplified Whole Life Carbon** (WLC) **framework** intended for integration into urban planning and construction permitting processes. Aligned with the aforementioned standards and frameworks, as well as the national initiative *Tools for Decarbonisation* [12, 13], the proposed approach defines a practical and consistent tool for evaluating building-related emissions in accordance with international methodologies. Finally, the framework builds upon LCA principles while introducing methods that enable its application during different phases of the building process.

2 The Simplified Whole Life Carbon Framework

2.1 Definition and Indicators

The simplified WLC framework aims to quantify greenhouse gas emissions from buildings throughout their life cycles. According to UNI EN 15978 [8], the life cycle of a building can be divided into several modules covering the Production of construction materials, Construction processes, Use, and End-of-Life scenarios (see Fig. 1).

The simplified WLC framework is the sum of two main components:

- **Embodied Carbon (EC):** CO_2eq emissions from Production (A1–A3), Construction (A4–A5), Replacement (B4), and End-of-Life (C2–C4).
- **Operational Carbon (OC):** CO_2eq emissions related to energy needs during the Use of the buildings (B6) for heating, domestic hot water, cooling, lighting, and movement.

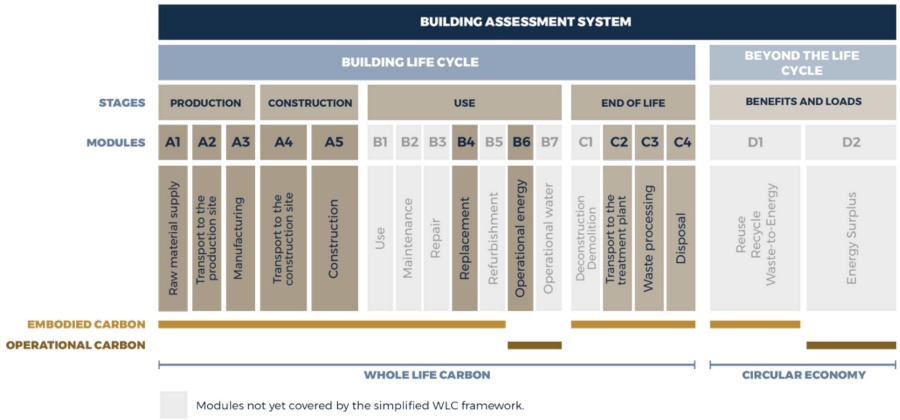


Fig. 1. Stages and modules covered by the WLC simplified framework.

2.2 Scope and Boundaries

The simplified WLC framework targets residential, office, school, healthcare, recreational, commercial, and sports buildings, excluding uses and typologies not covered by EPBD or the local building code.

The framework is designed for new buildings; however, with the appropriate selection of building elements and information on mechanical and electrical services, the method can also be used for buildings undergoing major retrofits.

The Functional Unit adopted is: $kgCO_2eq/(m^2$ HFA*year), where Heated Floor Area corresponds to the internal floor area of spaces served by the building's heating/cooling services.

The methodology also includes declared units, used in the accounting process for some modules. In this paper, a declared unit is represented by the Gross Floor Area (GFA), calculated in accordance with the EC for construction and installation processes (ECA5). The methodology is designed to support two main design and building processes:

- **Early Design.** The WLC framework provides a simplified approach to calculations, using generic datasets. This phase aims to support designers in comparing alternative design options and in identifying strategies to reduce embodied and operational carbon.
- **As-Built**. At this phase, calculations rely on more detailed information, including product-specific environmental data and updated quantities.

This two-step approach enables a progressive improvement of carbon estimates while ensuring consistency between design decisions and final reporting.

The reference period of the study (RSP) is set to align with the lifespan of buildings as defined in the main international standards, particularly Level(s) [8].

2.3 Modules and Calculation

The simplified WLC framework follows a structured procedure to ensure consistency across different building typologies:

- **Inventory Analysis:** material masses collection based on the "Design-as-Built (DaB)" project information.
- **Emissions Mapping:** assignment of emission factors (Generic or Specific/EPD) for each material to the accounted modules and stages.
- **Impact Calculation:** Application of the formulas across defined modules.

In the early design phase, emission factors are derived from generic datasets and literature-based values. In contrast, during the as-built phase, they are progressively replaced, where available, with product-specific data from Environmental Product Declarations (EPDs) to improve data quality and representativeness. Given the simplified nature of the framework, the results may be affected by uncertainty related to data quality and by assumptions concerning, among others, transport distances, replacement cycles, and end-of-life scenarios; these aspects will be examined through sensitivity analyses in the subsequent validation phase on real case studies."

The impact calculation refers to a defined number of life-cycle modules from UNI EN 15978, focusing on those assumed most relevant to municipal-level carbon accounting. Some modules were not considered because they were deemed difficult to account for. More specifically, priority was given to modules that can be accounted for using databases, certifications, and declarations (e.g., Environmental Product Declaration), or modules for which it is possible to establish assumptions compatible with local construction processes (e.g., average distances between the production site and the building construction site).

A1–A3 (Production): The modules account for raw material extraction and manufacturing. Calculations start from the DaB materials mass, adjusted by a production correction factor to account for site waste. If no specific information is available, a 9% value may be applied to all materials. For wood-based materials, the methodology accounts for biogenic carbon as a credit, provided it is not incinerated or landfilled at the End-of-Life (EoL).

Equation (1) defines the production $EC_{A1–A3}$:

$$EC_{A1-A3} = \sum_{J=1}^{n} \left[M_j \times f_{A1-A3,j} \times \left(1 + w_j\right) \right] \tag{1}$$

Where:

M_j = mass of the j-th material (kg)
$f_{A1–A3,\,j}$ = emission factor of the j-th material ($kgCO_2eq/kg$)
w_j = production factor of the j-th material (%)

A4 (Transport): The module uses standardised emission factors to estimate the impact of material transportation. Equation (2) defines the transport EC_{A4}:

$$EC_{A4} = \sum_{J=1}^{n} \left(M_j \times dj \times f_{trans,j} \right) \tag{2}$$

Where:

M_j = mass of the j-th material (kg)
dj = distance for transport from the factory gate to the construction site of the j-th material (km)
$f_{trans,\,j}$ = transport mode emission factor of the j-th material ($kgCO_2eq/km$)

A5 (Installation/Construction): The module accounts for emissions from on-site assembly and the management of construction waste. The installation is estimated via standardised factors based on the building's Gross Floor Area (GFA) or specific site equipment data. Equation (3) defines the Installation/Construction EC_{A5}:

$$EC_{A5} = GFA \times k_{A5} \tag{3}$$

Where:

GFA = Gross Floor Area (m^2)
k_{A5} = installation emission factor ($kgCO_2eq/GFA$)

B4 (Replacement): The module considers the estimated service life of components. Materials with a lifespan shorter than the RSP must be replaced, thereby increasing EC. "Roundup" is an operation that takes a number and rounds it to the nearest integer that is greater than or equal to that number. For instance, in the roundup, the result is 3, even though 2.5 is exactly in the middle; it always rounds up to the next whole number. Equation (4) defines the number of replacements and Eq. (5) the CO_2eq emissions released by the new materials installed EC_{B4}:

$$N_j = ROUNDUP\left(\frac{RSP}{SL_j} \right) \tag{4}$$

Where:

roundup = a function that increases a number to the nearest whole number
RSP = Reference Study Period (year)
$SL_{\,j}$ = Service Life of the j-th material (year)

$$EC_{B4} = \sum\nolimits_{J=1}^{n} \left[\left(EC_{A1-A3,j} + EC_{A4,j} \right) \times N_j \right] \tag{5}$$

Where:

$EC_{A1–A3,\,j}$ = emissions released from the j-th material's Production, see Eq. (1) ($kgCO_2eq$)
$EC_{A4,\,j}$ = emissions released from the j-th material's Transport to the construction site, see Eq. (2) ($kgCO_2eq$)
N_j = number of replacements of the j-th material within the RSP (number)

B6 (Operational Energy): The module is based on the energy performance certificates and predicted energy demand for the building's operation (e.g. Energy Performance Certificate). Equation (6) defines the Operational Carbon OC_{B6}:

$$OC_{B6} = \sum_{K=1}^{n} \left(Q_{B6,k} \times f_{B6,k}\right) \tag{6}$$

Where:

$OE_{B6,\,k}$ = energy needs of the building, including heating-cooling, ventilation, lightning (kWh/year)
$f_{B6,\,k}$ = emission factor of the k-th energy carrier ($kgCO_2eq/kWh$)

End-of-Life (C2–C4): These modules include waste transport (C2), waste treatment (C3), and final disposal (C4). The methodology requires determining $kgCO_2eq$ for modules C2–C4 by applying emissions factors to the waste mass. This mass is calculated by considering the volumes of waste produced by the Installation/Construction (A5), the Replacement (B4), and the building's EoL (C). Equation (7) defines the total waste mass:

$$M_{waste,j} = \sum_{J=1}^{n} \left[\left(M_j \times w_j\right) + \left(M_j \times N_j\right) + M_j\right] \tag{7}$$

Where:

M_j = mass of the j-th material (kg)
w_j = production factor of the j-th material (%), see Eq. (1)
N_j = number of replacements of the j-th material within the RSP (number), see Eq. (4)

Based on the waste mass, the transport to the treatment plant (C2) is calculated by assuming a fixed distance of 30 km. The CO_2eq emissions can be figured out by applying Eq. (2). At the same time, the waste processing (C3) and final disposal (C4) are performed together. It is based on a conservative EoL scenario of 30% disposal and 70% recycling, in line with EU waste policy and plans. Equation (8) defines the $EC_{C3–C4}$:

$$EC_{C3-C4} = \sum_{J=1}^{n} \left(M_{waste,j} \times 0,3\right) \times f_{C3-C4\ \mathrm{rec},j} + \left(M_{waste,j} \times 0,7\right) \times f_{C3-C4\ \mathrm{dis},j} \tag{8}$$

Where:

$M_{waste,\,j}$ = mass of the j-th waste (kg)
$f_{C3–C4\ rec,\,j}$ = emission factor of the j-th waste recycled ($kgCO_2eq/kg$)
$f_{C3–C4\ dis,\,j}$ = emission factor of the j-th waste landfilled ($kgCO_2eq/kg$)

2.4 The Total Whole Life Carbon

The total WLC building is the sum of EC and OC contributions, normalised to HFA and RSP. Equation (9) defines the WLC:

$$WLC = \frac{\sum(EC_{A1-A3} + EC_{A4} + EC_{A5} + EC_{B4} + OC_{B6} + EC_{C3-C4})}{HFA \times RSP} \quad (9)$$

Where:

$EC_{A1–A3}$ = emissions from Production ($kgCO_2eq$)
EC_{A4} = emissions from Transport of material to the construction site ($kgCO_2eq$)
EC_{A5} = emissions from Installation/Construction ($kgCO_2eq$)
EC_{B4} = emissions from Replacement ($kgCO_2eq$)
OC_{B6} = emissions from Operational Energy ($kgCO_2eq$)
EC_{C2} = emissions from Transport of waste to the treatment plant ($kgCO_2eq$)
$EC_{C3–C4}$ = emissions from the EoL scenario of waste ($kgCO_2eq$)
HFA = Total square meters of Heated Floor Area (m^2)
RSP = Reference Study Period (50 years)

A crucial step in the research is setting appropriate benchmarks for assessing the results achieved by the different buildings. Owing to ongoing testing of the methodology, a preliminary step involved setting an initial threshold value of 800 $kgCO_2eq/m^2$HFA*year for residential buildings, and 900 $kgCO_2eq/m^2$HFA*year for other uses (e.g. offices, schools, etc.) based on recent research conducted in Mediterranean EU countries [14, 15]. This value can be understood as an intermediate milestone in long-term carbon-reduction scenarios.

3 The Whole Life Carbon for Urban Climate Action

The simplified framework is designed to enable the integration of WLC assessment into urban climate action.

First and foremost, it is intended to provide a user-friendly, accessible framework for non-LCA experts, built on databases, certifications, and declarations available online, many of which are open source. The assumptions used to account for certain stages and modules are based on international standards and studies.

Second, by adopting a consistent calculation and reporting structure, the simplified framework is expected to improve the comparability of building projects by establishing a methodology for calculating and reporting emissions; the latter is particularly relevant for municipalities seeking to monitor the carbon performance of construction activities within their territories.

Third, the use of simplified data structures facilitates integrating WLC assessment into early design stages, enabling designers to evaluate the carbon implications of alternative materials and construction strategies.

Finally, the framework may support the future integration of EC and OC metrics into municipal climate policies and support the development of regulatory instruments to reduce building-related emissions.

4 Conclusion

The simplified WLC framework provides a pragmatic yet rigorous tool for urban climate assessments. Nevertheless, the practical application of LCA-based methods in design and policy contexts remains challenging due to their complexity and data requirements. Data availability and consistency remain critical issues, particularly for product-specific environmental data. In addition, future developments may benefit from integrating digital tools such as Building Information Modelling (BIM) and digital twins to enable automated data exchange.

The methodology has not yet been validated through applications to real buildings. At this stage, preliminary analyses have been conducted on representative building archetypes to test the internal consistency of the calculation structure and to support the definition of initial thresholds. The empirical validation of the framework through applications to real building cases constitutes the next phase of the research.

Future research targets include applying the WLC framework to a sample of different building types; this will enable the establishment of a benchmark and, subsequently, the development of a rating system comparable to the one currently used to assess energy performance.

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