

Integrating life cycle assessment and building information modelling: A purpose-driven approach

Maria Teresa H.A. Ferreira ^{*} , António Aguiar Costa, José Dinis Silvestre

CERIS, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais 1, 1049-001, Lisbon, Portugal

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ABSTRACT

Building information modelling (BIM) has become a transformative methodology in architecture, engineering, and construction (AEC) by integrating collaborative design, construction, and facility management. This paper investigates the BIM's evolving role across design phases, with a particular focus on the level of information need (LOIN) and its integration into life cycle assessment (LCA). Although the design process progresses through distinct phases requiring tailored information and model development, it currently lacks an intermediate LCA capable of supporting early optimization of design solutions. To address this gap, the study examines how BIM adaptability and the structured use of LOIN through progressive detailing of components can enhance information consistency, efficiency and collaboration throughout the project timeline. A standardized, purpose-driven framework is proposed to manage data requirements and support the integration of LCA within BIM workflows. The proposed framework enables informed decision-making, improves environmental performance, and supports phase-appropriate data accuracy across the life cycle (LC). Its novelty lies in incorporating average Environmental Product Declaration, improving BIM-LCA interoperability, and facilitating data automation via a dedicated tool. The approach is validated through a real-life case study, demonstrating the practical benefits of a LOIN-based LCA approach. In conclusion, the findings show that BIM has the potential to harmonize design phases, LOIN, and LCA, fostering collaboration, efficiency, and sustainability. The resulting purpose-driven framework provides stakeholders with a structured method for adjusting the LOIN across design phases and integrating it with LCA requirements to act in early phases to support climate and construction related environmental impact mitigation.

1. Introduction

Building information modelling (BIM) has transformed the architecture, engineering, and construction (AEC) industry by fostering collaboration and data integration throughout the project life cycle (LC). A key aspect of maximizing BIM potential lies in understanding and defining the level of information need (LOIN), which governs the granularity and precision of the data required at each project phase. This research investigates the interplay between LOIN, level of development (LOD), and design phases, analysing their impact on LC considerations and life cycle assessment (LCA).

The AEC industry has embraced BIM as a powerful methodology for improving project efficiency and stakeholder coordination. However, integrating LOIN into BIM workflows remains a critical challenge, especially when addressing long-term sustainability goals.

^{*} Corresponding author.

E-mail address: teresafferreira@tecnico.ulisboa.pt (M.T.H.A. Ferreira).

List of acronyms

ADPf -	Abiotic depletion potential for fossil fuels
ADPm -	Abiotic depletion potential for non-fossil resources, minerals, and metals
AEC -	Architecture engineering and construction
AP -	Acidification potential
BEP -	BIM execution plan
BIM -	Building information modelling
BoQ -	Bill of quantities
CLT -	Cross-laminated timber
DD -	Detail design
EP -	Eutrophication potential
EPf -	EP, a fraction of nutrients reaching freshwater end compartment
EPm -	EP fraction of nutrients reaching marine end compartment
EPT -	EP accumulated exceedance EP terrestrial
EPBD -	European performance of buildings directive
EPD -	Environmental product declaration
EU -	European Union
GHG -	Greenhouse gas
GWP -	Global warming potential
GWPb -	GWP biogenic
GWPf -	GWP fossil
GWPI -	GWP land use and land use change
GWPt -	GWP total
IBU -	<i>Institut Bauen und Umwelt e.V.</i>
LC -	Life cycle
LCA -	Life cycle assessment
LCIA -	Life cycle impact assessment
LOD -	Level of development
LOG -	Level of geometry
LOI -	Level of information
LOIN -	Level of information need
MPS -	Model progression specification
NZEB -	Nearly zero energy buildings
ODP -	Ozone depletion potential
PD -	Preliminary design
PENRT -	Primary energy resources – non-renewable (total)
PERT -	Primary energy resources – renewable (total)
POCP -	Photochemical ozone creation potential
RE -	Environmental regulation
WDP -	Water (user) deprivation potential, deprivation-weighted water consumption
WF -	Wood frame

This study delves into how well-defined information requirements can optimize decision-making across the design and construction phases, ensuring that data richness aligns with the needs of LC management.

1.1. Literature review

LCA has become a cornerstone of sustainability evaluation in the AEC industry, providing a standardized framework to assess the environmental impacts of buildings across their entire LC. Originating with the ISO 14040 [1] standard in the late 1990s [2], LCA has since evolved through frameworks such as EN 15978 [3], which specifically addresses building sustainability assessments [3]. The four key phases of LCA—goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation—form a robust structure for evaluating environmental performance [1]. However, this process requires accurate, context-specific data on materials and components, often derived from the bill of quantities (BoQ). The challenge of acquiring and managing such data remains a major barrier to its practical implementation, highlighting the need for more streamlined and interoperable information management systems [4,5].

To address these challenges, EPDs have emerged as critical documents for LCA applications. Governed by the ISO 14025 [6] and EN 15804 [7] standards, EPDs provide transparent and verified data about the environmental impacts of materials and processes. The EPD process follows a structured methodology: first, selecting product category rules (PCRs), which define how LCA should be conducted;

second, performing an LCA study, which assesses the environmental impact of a product, material, or service throughout its LC [6]; third, compiling the results into an EPD format; fourth, undergoing third-party verification; and, finally, registering and publishing the EPD, making it freely accessible on platforms such as Environdec [8].

Despite their utility, EPDs are often specific to individual products or manufacturers, limiting their use at early design phases or during public procurement processes where manufacturer-neutral data are needed. This has led to proposals such as the Native LCA methodology [9], which adapts EPDs and other data sources to create generic datasets specific to national or project contexts, enhancing their applicability while maintaining reliability. However, even with EPDs, the complexity of data structures and the fragmented nature of information management pose significant challenges for effectively integrating LCA into design decision-making phases and processes.

One of the significant gaps identified is the lack of generic EPDs, i.e., average EPDs. While existing EPDs are useful for specific products, materials, or systems, they cater primarily to specific manufacturers, making them highly applicable in Stage A5 (manufacturing and construction) or technical design phases for private clients. However, in public competitions where specifying a manufacturer is not allowed, the absence of average EPDs poses a major challenge for confidentiality purposes where generic environmental goals could be a plus.

The LCA has been extensively employed to evaluate the environmental impacts of buildings; however, the reliability of its results can be influenced by various sources of uncertainty [10,11], as well as challenges related to technological integration, such as BIM [12–14]. Despite these limitations, previous studies have shown that LCA remains a robust method for distinguishing between projects exhibiting environmental impact differences exceeding 20 % [10]. Hoxha et al. [10] further emphasized that the degree of uncertainty tends to decrease as the design process advances.

The French government has implemented RE2020 environmental regulation (RE) [15], a new energy and environmental framework for new buildings, replacing the previous RT2012 [16] thermal regulation. This regulation introduces a holistic approach by addressing both energy consumption and carbon emissions, including those from the construction phase [15]. RE2020 [15] is designed to guide the future of French construction while aligning with national carbon neutrality goals. It focuses on three main objectives: energy efficiency and decarbonization, i.e., reducing energy consumption and promoting renewable energy sources; reducing carbon impact, i.e., assessing greenhouse gas (GHG) emissions across the entire LC of a building, from material production to end-of-life; and thermal comfort during heat waves, i.e., ensuring that buildings remain liveable despite increasing temperatures. Transport is included in the environmental assessment of buildings, but it is not factored into compliance indicators. The environmental impact of materials and construction processes is assessed through LCA using data from the INIES database (www.inies.fr). This includes EPDs. The RE2020 [15] regulation represents a ground-breaking shift towards a more sustainable and low-carbon building sector in France. By integrating LCA, improving energy efficiency, and enforcing stricter carbon emission limits, this regulation aligns France with global climate commitments while ensuring high-quality, comfortable, and energy-efficient buildings for the future.

BIM offers a potential solution to these issues, with its ability to centralize and manage data throughout the LC of a building [17, 18]. BIM-based LCA is increasingly seen as a game changer for sustainability assessments. By linking BIM models to LCA databases, environmental impact assessments can be performed more efficiently and with greater accuracy. Specifying the information requirements and purposes for each LCA design phase enabled detailed and precise data integration, enhancing the reliability of the LCA outputs. Additionally, the dynamic nature of BIM models allows for parametric analyses, enabling designers to explore multiple scenarios and optimize decisions for environmental performance. However, the effective integration of BIM and LCA requires a shift from static data models to purpose-driven approaches that prioritize information relevance and applicability at each phase of the design and construction process.

This is where the concept of LOIN becomes crucial. Introduced through the EN 17412–1:2020 [19] standard, LOIN represents a shift from predefined levels, such as LOD [20], to a more flexible and purpose-driven framework. The LOIN ensures that the information provided is tailored to the specific requirements of each project phase, aligning data precision and granularity with decision-making needs. By focusing on clear information definitions, traceability, and validation processes, the LOIN addresses many of the ambiguities and inefficiencies associated with traditional LOD-based frameworks. This approach not only facilitates better information management but also supports the integration of BIM and LCA by ensuring that the right information is available at the right time for the right purpose.

The concept of LOD, initially defined as the "level of detail," was introduced in 2004. The evolution from LOD to LOIN reflects a broader effort to enhance the clarity and applicability of information management standards in the AEC industry. Initially introduced as a "level of detail" in 2004, it was introduced in 2004 as part of the Model Progression Specification (MPS), a framework for BIM developed by the software company Vico, which was later integrated into Trimble. The concept of LOD evolved through frameworks such as the American Institute of Architects' (AIA) [20] classification system and the UK's PAS 1192–2 [21,22], which introduced "level of definition" as a dual-dimensional framework encompassing graphical and nongraphical content. Over time, related terms such as level of geometry (LOG) and level of information (LOI) have been developed [23], adding complexity but also creating confusion because of the extensive lexicon and the number of different terminologies. The advent of LOIN represents a decisive step towards resolving these challenges by focusing on purpose-driven information requirements rather than static classifications. This shift is essential for advancing the integration of BIM, LCA, and EPDs, ultimately supporting the AEC industry's pursuit of digital and environmental sustainability through the twin transition.

The recast of the Energy Performance of Buildings Directive (EPBD) currently has to be implemented in each European country, which will require defining rules for calculating the embodied GWP of buildings, and this article is also a contribution in that regard [24].

This research aims to address this gap by exploring how each EPD relates to design phases and LOIN per design phase, offering

solutions to enhance the availability and usability of average datasets. The framework encompasses a purpose-driven approach for LCA per design phase and its implementation into a BIM tool and evaluation in a case study testing different material options during the design phases.

1.2. Research aim and scope

This paper focuses on aligning information requirements with BIM practices to provide new insights into how the right information at the right time can influence LC and LCA outcomes, including a proposal of an average Environmental Product Declaration (EPD) for early design phases, when material decisions are being made and the respective environmental mitigations can be implemented. In addition, the present work addresses solutions to the problem of public procurements when no specific material from a given manufacturer can be selected but environmental considerations should be in place.

The discussion and importance surrounding the purpose-driven approach for LCA lie in identifying the information requirements for each design phase and the appropriateness of different analyses to be performed in each phase. In that sense, the EPDS is highly relevant within the context of sustainable construction. However, framing this discussion within a purpose-driven approach is essential, as this perspective raises critical questions regarding the development of a framework for an intermediate level of assessment, i.e., the proposed average EPDs for early project phases where specific details remain unknown. Addressing this challenge is crucial to ensure that early-stage decision-making is both informed and aligned with the project's environmental and strategic objectives. A structured approach to integrate frameworks at these preliminary phases could enhance sustainability assessments and improve LC performance predictions.

This study analyses the hypothesis-driven research questions.

- How can the LCA be improved during the design process, starting in early design phases?
- Does acting in early design phases have advantages in the optimization of LCA in construction?

The hypothesis formulated in the present work is based on the proposal of having different information requirements for LCA in different phases of the project. In particular, the proposal addresses how this requirement can progressively add environmental benefits to better decision-making integrated in the design phases, instead of performing LCA only in the last phase of the project development. The proposal considers the use of average data to perform an early design of environmental LCA to study different possibilities and different materials for optimized solutions early in the process and, in the later phase, compare them with final results in detail design. The objective is to optimize the environmental impact of the building sector in terms of mitigation early in the design phases, where material decisions can be made, instead of traditional LCA studies in detail design. Accordingly, the first part of this article introduces a framework for aligning information requirements with LCA processes, utilizing average EPDs in the context of wood materials. The second part evaluates the scalability and applicability of the framework through a real-life architectural case study. The approach advocates the use of differentiated LCA data tailored to the specific design phase, which aligns with the evolving information requirements across the project timeline. It further explores various material options throughout the design phases and

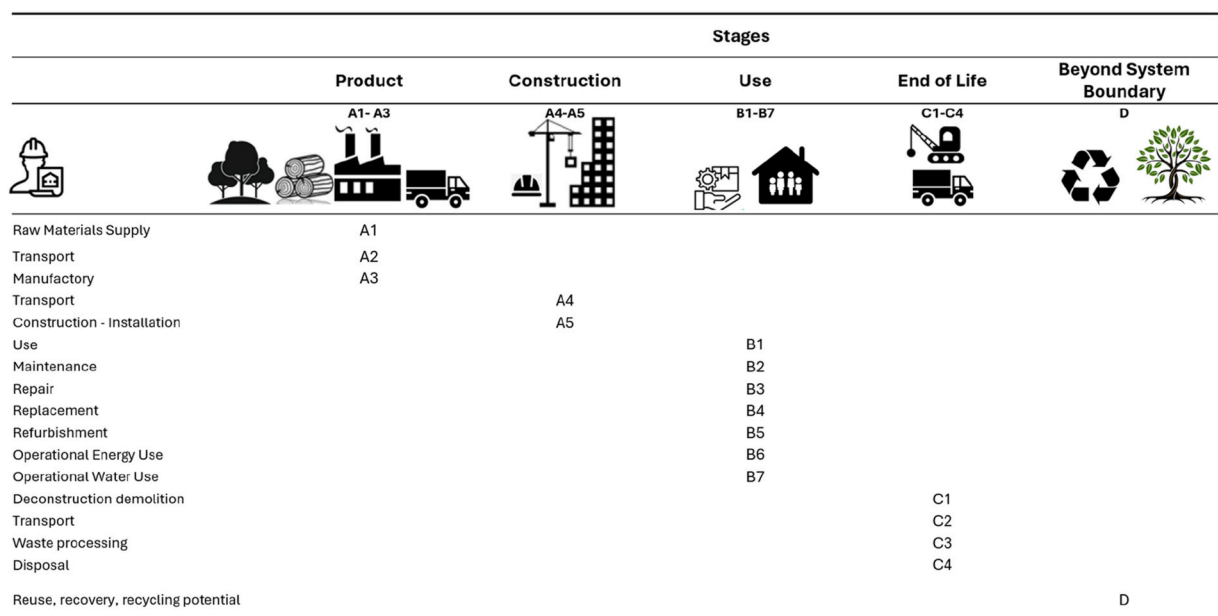


Fig. 1. LCA Stages A–D used to classify data, according to EN 15978 and EN 15804 [3,7].

compares LCA outcomes across the design phases, highlighting the phase-specific benefits of this alignment.

2. Research methodology

The current investigation addresses the purpose-driven challenge of integrating BIM with LCA to enhance sustainability evaluations across construction projects. The proposed methodology leverages the LOIN approach defined in the EN 17412–1:2020 [19] standard to ensure precise alignment between data requirements and project-specific objectives. By prioritizing data relevance over quantity, this article establishes a structured workflow that integrates BIM processes with the analytical demands of LCA while focusing on environmental sustainability objectives.

2.1. Integration of design phases with LCA requirements

Construction projects are characterized by a sequence of design phases, from strategic definition to the post-construction phase. Each phase necessitates distinct information, which evolves in granularity and relevance as the project progresses. The work reported herein maps these design phases to the LC stages (Fig. 1) defined in EN 15804 [7].

- **Stages A1–A3:** Material extraction, transport, and manufacturing;
- **Stages A4–A5:** Construction and installation processes;
- **Stage B:** Operational efficiency, including maintenance and replacement impacts;
- **Stages C–D:** End-of-life processes, reuse, recovery, and recycling.

The mapping process identifies the data required at each project phase, ensuring alignment with LOIN principles. This alignment facilitates the progressive integration of sustainability metrics into the project workflow. For example, early phases utilize average EPDs to inform preliminary decisions, whereas later phases incorporate specific EPDs to increase the precision of environmental impact calculations.

2.2. Adoption of the LOIN framework

The LOIN method replaces the LOD concept, which focuses on tailoring data delivery to specific project purposes rather than predefined levels of granularity. This framework is implemented across three domains to address the distinct needs of LCA.

- **Geometric Information:** Spatial and material characteristics of building components, sufficient for LCA at each project milestone;
- **Alphanumeric Information:** LC attributes such as material properties, performance metrics, and environmental impacts;
- **Documentation:** Supplementary files, including EPDs and compliance certifications, to ensure data traceability and validation.

The framework of LOIN is applied iteratively, ensuring that the provided data are relevant and purposeful. For example, during early design phases, the focus is on simplified geometric models and indicative material impacts, where mitigation can be implemented. In contrast, advanced phases require precise data for LC performance evaluations and regulatory compliance.

2.3. Purpose-driven approach to LCA data management

The research methodology adopts purpose-driven information requirements for each project milestone. This approach ensures compatibility with stakeholder workflows, supporting both human and machine interpretations of data. Examples include the following.

- Early-phase conceptual models prioritize generic data to broadly evaluate sustainability impacts, enabling the preliminary LCA and the testing of different materials and design options to have preliminary studies of the LCA impacts aiming to optimize solutions;
- As the project progresses, more detailed and validated data are incorporated, enabling a precise LCA and informed decision-making along with a detailed model.

This dynamic application of LOIN ensures efficient data exchange across disciplines, facilitating seamless collaboration among architects, engineers, contractors, and other stakeholders.

2.4. Integration of BIM workflows with LCA stages

The methodologic approach integrates BIM workflows with the LC stages defined in EN 15804 to achieve comprehensive sustainability assessments [3,7]. The Level(s) framework by the European Commission [25,26] serves as a guiding structure for this integration, aligning BIM-based data management with sustainability indicators such as greenhouse gas emissions and resource efficiency. This alignment ensures the following.

- BIM models evolve to meet the information requirements of each LC stage;

- Data granularity is adapted to the needs of the project phase, bridging early-phase uncertainties with detailed evaluations in later phases.

This integration not only enhances the practical applicability of LCA but also ensures that the entire LC of the building is considered in sustainability assessments.

The purpose-driven information requirements, including the LOIN approach defined in the standards [19], were applied to the LCA, defining the requirements for each LCA stage and each corresponding assessment, which were integrated with necessary data from each project design phase.

3. Framework development

3.1. LCA and project phase alignment

The research approach integrates design phases with LCA requirements highlights the need for a structured alignment of environmental objectives with decision-making processes throughout the project LC. Traditionally, LCA stages (A–D, as defined in EN 15804 [7] (Fig. 1)) are applied predominantly during the manufacturing and construction phases (A1–A5), Fig. 2. This late-phase implementation limits opportunities to mitigate environmental impacts, as many material and system choices are finalized earlier in the design phases, such as during concept design and technical design.

The findings from this article underline the need to incorporate LCA considerations from the early phases of design to align with sustainability targets set by European Union (EU) directives. Aligning LCA with the project's conceptual and technical design phases [27] allows the evaluation of material and system alternatives when changes can still be made. Fig. 2 illustrates the relationship between the traditional design phases and LCA stages, emphasizing the need for current practices to account for environmental decisions earlier in the process and propose a timeline where LCA considerations begin at early design phases.

The Level(s) framework [28] of the EU offers a structured methodology to bridge the gap between the design phases and LCA stages. It divides the process into three levels of engagement.

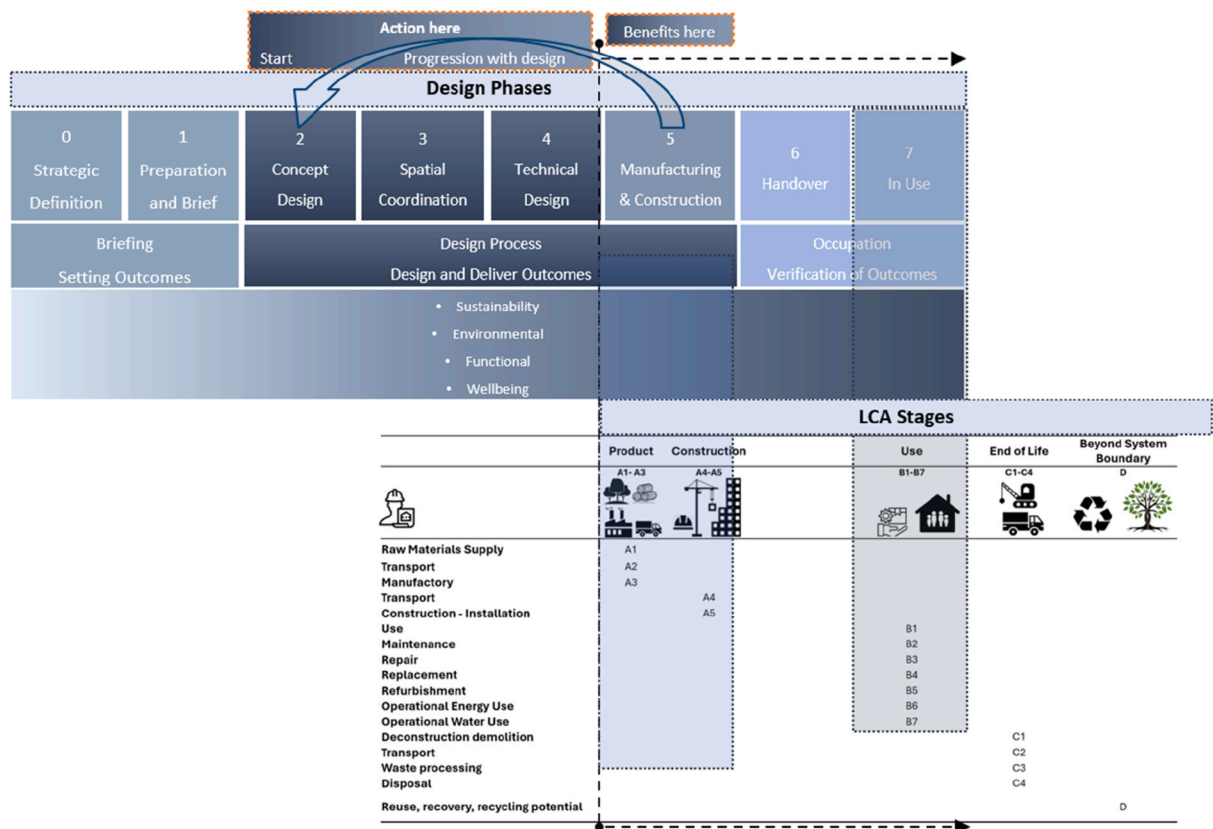


Fig. 2. Design phases versus LCA Stages A–D: shows where to act, and where the benefits are.

1. **Level 1-Concept Design:** During the project's definition and briefing phase, sustainability goals are qualitatively assessed using a structured Yes/No questionnaire. This phase aims to raise awareness of sustainability considerations and establish clear environmental targets at the outset;
2. **Level 2-Detail Design and Tendering:** At this phase, quantitative assessments are introduced, enabling detailed calculations of environmental impacts and supporting material and system optimization to achieve sustainability goals;
3. **Level 3-In-Use Phase:** A building's operational performance is evaluated by comparing its actual impacts with earlier estimations. The lessons learned from these comparisons provide valuable insights for future projects.

Fig. 3 demonstrate the relationships between the design phases (traditional, [27]), BIM development, and Level(s) framework phases, integrating in the last rows the proposed design phases for BIM and LCA integration. This figure highlights the integration of sustainability objectives into the BIM Execution Plan (BEP). Setting up the sustainability targets aligned with Level 1 of the Level(s) framework, which serves as the operational framework for project teams. By embedding LCA goals and strategies into the BEP at the conceptual phase, the study ensures that environmental objectives are maintained consistently throughout the project LC.

3.2. LOIN at each BIM-LCA phases

Historically, the term LOD was used to describe the aggregation of geometric and alphanumeric information in a model. However, the EN 17412–1:2020 [19] standard redefines this approach under the LOIN framework, emphasizing purpose-driven information delivery. Unlike LOD, LOIN focuses on tailoring information precision to specific project milestones and objectives, ensuring efficiency and clarity throughout the LC [19]. The traditional reliance on the LOD framework is insufficient to meet the evolving information requirements of LCA. Instead, the current research proposes adopting the LOIN framework, which emphasizes purpose-driven data delivery tailored to specific project phases and environmental objectives.

The purpose-driven information requirements proposed, aligned with LOIN, structure information into three domains already referred to and listed below, including the proposed field for LCA integration.

- **Geometric Information:** Volumetric representation, location, and spatial and material properties relevant to LCA;
- **Alphanumeric Information:** Environmental data such as global warming potential (GWP): GWP-fossil (GWPf), GWP-biogenic (GWPb), GWP-land use change (GWPl), and GWP-total (GWPt). Additional indicators include ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), EP-freshwater (EPf), EP-marine (EPm), EP-terrestrial (EPt), POCP,

Design Phases							
0 Strategic Definition	1 Preparation and Brief	2 Concept Design	3 Spatial Coordination	4 Technical Design	5 Manufacturing & Construction	6 Handover	7 In Use
BIM							
0/ 1 - Planning • Aim and objectives • Sustainability strategies • Functionalities • Team and workflows • BEP – BIM Execution Plan • Common Data Environment		2/ 3/ 4 - Design • Building design, from conceptual to detailed • Documentation and schedules • Compatibility tests • Analysis including Sustainability LCA • Improve material options • Optimization			5 – Building • Construction starts • Potential for prefabrication, assembly on site. • Logistics and suppliers		6/ 7 – Operating • Provide BIM Model after the building is finished to be used during its service life and use BIM Data for: • Operations and maintenance • Cost-effective renovations • Efficient deconstruction
Level(s) EU Framework							
Level 1 • Project definition, brief • Concept design		Level 2 • Outline design (spatial planning and permitting) • Detailed design (tendering) • Technical design (construction)				Level 3 • As-built design • Commissioning and testing • Completion and handover • Occupation and use	
Proposed Design Phases for BIM and LCA integration							
Briefing – Conceptual Design, Setting Outcomes		Design Process Detail Design, construction and Deliver Outcomes LCA: LC Stages A1-A5				Occupation – As-built/ in use Verification of Outcomes	
1- Planning/ BEP		2 A - Preliminary design		2 B - Detailed design		3- Delivered/ In use	

Fig. 3. Design phases versus BIM and the Level(s) EU framework, highlighting the main objectives of each phase. Addressing the issue of LCA, BIM, EU directives and the proposal of its integration along the design phases. Including the suggested naming and conventions for the additional phase.

abiotic depletion potential (ADP), ADP- minerals & metals (ADPm) and ADP-fossil (ADPf), water (user) deprivation potential (WDP), embodied energy metrics, primary energy resources-renewable (total) (PERT), and primary energy resources non-renewable (total) (PENRT).

- **Documentation:** Supporting documents such as EPDs, regulatory compliance certifications, and sustainability benchmarks.

Integrating LOIN into the design phases ensures that information is delivered at the precision needed to meet the LCA objectives without overburdening the design phases. For example, during the concept design phase, simplified geometric models with generic environmental data (e.g., average EPDs) are sufficient for preliminary sustainability evaluations. As the design progresses to the technical design and spatial coordination phases, more detailed geometric and alphanumeric data, including specific material properties and verified EPDs, are needed. This progression is visualized in Fig. 4, which details the proposed LOIN requirements per phase as well as the proposed data management, EPD, per the proposed design phase, which are all aligned with the EU directives for sustainability [25,26,29,30].

3.3. Proposed framework for BIM and LCA integration aligned with LOIN

The proposed framework provides a structured pathway for incorporating sustainability into the design phases, progressing from qualitative goal setting at Level 1 to quantitative impact evaluations at Level 2, which are divided into two subphases (preliminary design, detailed design), and operational performance monitoring at Level 3. At Level 2, where detailed calculations of LC impacts, such as GWP, are performed, the availability of EPDs becomes essential. These declarations provide the specific material and system data required to evaluate environmental impacts accurately (Fig. 4).

The LOIN approach demonstrates great adaptability when applied to LCA. This proposal highlights its effectiveness in managing diverse information needs across project LC stages. For example.

1. **Level 1-Planning Phase (BEP):** Establishing sustainability objectives and LCA goals through qualitative reports and initial benchmarks;
2. **Level 2a-Preliminary Design Phase:** Incorporating generic framework representations and average EPDs to calculate preliminary GWP values and other environmental indicators, enabling the possibility of testing different scenarios for optimized solutions;
3. **Level 2b-Detail Design Phase:** Delivering detailed models with material layers, alphanumeric data, and specific EPDs to support quantitative LCA calculations;

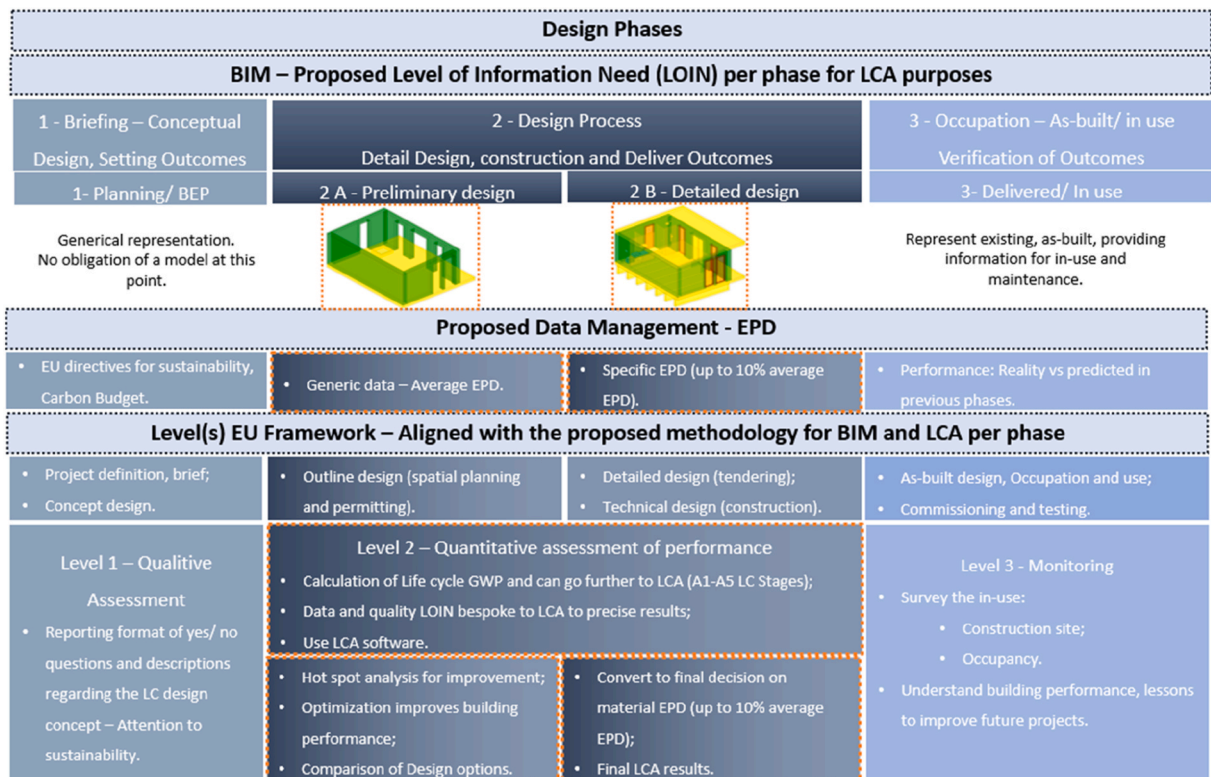


Fig. 4. Proposed framework for BIM and LCA integration across the design phases, aligned with the LOIN and Level(s) EU framework. Addressing the issue of which data to use in each level of assessment. Proposed hotspots are highlighted in orange-dotted frames.

4. Level 3-In-Use Phase: Providing as-constructed models and LCA verification, enabling performance comparisons and lessons learned for future projects.

This structured progression ensures that each phase's information aligns with the intended purpose, enhancing the reliability of LCA outcomes and supporting decision-making. This approach also bridges information requirements between construction, facility management, and sustainability initiatives, as shown in Table 1.

The ideal scenario provides freely available average EPDs for all common material types. However, given the current limitations, the proposed framework enables practitioners to derive reliable data for eco-design and LCA analyses. This ensures compliance with public procurement requirements and promotes consistency and transparency in sustainability evaluations across diverse project contexts. As regional and global EPD database advancements continue, this framework provides a scalable solution for integrating LCA into the broader framework of BIM-based sustainability assessments.

3.4. Modelling, information management, and classification system

The process of bringing together LCA into BIM workflows is a project requirement that fundamentally relies on precise modelling, effective information management, and standardized classification systems. Accurate representation of materials and design constituents is essential to ensure reliable environmental impact assessments. Critical attributes such as thickness, height, volume, and area must be defined with precision, as inaccuracies or oversimplifications can lead to unreliable LCA outputs. Rigorous modelling has been shown to significantly increase the accuracy of LCA results, as demonstrated in previous studies [31–34].

To achieve precise LCA results, each material layer in a construction element, such as a wall, must be modelled as an individual element. This ensures that the model reflects real-world construction practices. However, if elements such as plasterboard are inaccurately extended beyond their intended dimensions (e.g., from the false ceiling to the slab, as shown in Fig. 5), the BIM tool may overestimate the environmental and economic impacts of that material. Therefore, modelling materials as separate elements, precisely reflecting their actual construction dimensions and behaviour, is recommended to avoid unnecessary overestimations.

Table 1

Adaptation of specified LOID methods from annexes of EN 17412–1, 2020 [19] for LCA use per design phase, for the case of a wall. Addressing the problem of BIM and LCA standards interoperability.

	Information Delivery Milestone	Planning/BEP	Preliminary Design	Detail Design	Delivered/In use
		LCA environmental guides and objectives	GWP—first generic	LCA—detailed quantitative report	LCA results verification and lessons learned
Example 1— LOIN for LCA use for the case of a wall	Actor	Architect			
	1 Object	Overall premises questionnaire (for project)	Wall		
	1.1 Geometrical information:	Not requested	Generic wall	Detailed wall	As-built
	1.1.1 Detail:		Simplified representation including openings	Material by layer	
	1.1.2 Dimensionality		3D		
	1.1.3 Location		Absolute		
	1.1.4 Appearance		Overall volume	Realistic with materials definition	As-built
	1.1.5 Parametric behaviour				
	1.2 Alphanumerical information:		GWP generic as proposed, GWPt, GWPf, GWPl, and GWPb	GWPt, GWPf, GWPl, GWPb, ODP, POCP, AP, EP, EPf, EPm, ADPf, ADPm, and WDP	
	1.2.1 Identification	LCA objectives	Benchmark suggestions	Improvement spots	
	1.2.2 Information content	Qualitative report	Quantitative report, including: type, quantity, area, volume, composition material (via type), and classification	Quantitative report, including: type, quantity, area, volume, composition material (via type), and classification	
	1.3 Documentation	Not requested	LCA reports per phase		
	1.3.1 Set of documents		Average EPD	EPD per material or construction system	Verification and comparative study between the LCA reported at previous phases and as constructed, including the lessons learned report

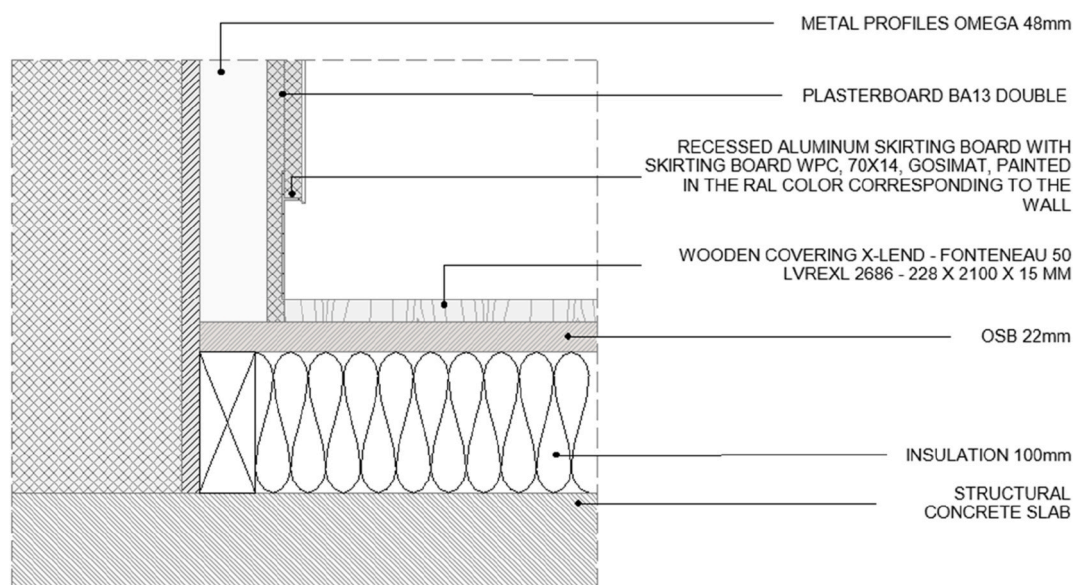


Fig. 5. Detail section, skirting board, and floor.

Further accuracy requires the correct use of BIM categories for all elements (e.g., walls, floors, doors). However, certain software limitations may necessitate the use of categories such as "railing" for unconventional purposes such as fencing. These limitations underline the importance of adopting robust classification systems to maintain consistency and standardization across the BIM model.

To address this, a classification system must be applied, such as the Uniclass classification system for categorizing BIM elements. Uniclass, or the chosen classification system, should ensure that each component is assigned to the correct category (e.g., walls, floors, windows), facilitating interoperability and data consistency throughout the design and construction phases. A standardized classification system is equally critical for integrating EPDs into BIM workflows.

3.5. Data availability and the need for generic data for the alignment of BIM and LCA methodologies

Challenges arise when specific EPDs are unavailable for certain products, especially in public procurement contexts where the use of generic data is often mandated to maintain neutrality among manufacturers and in the preliminary phase when products to be used are not yet decided upon and generic data are needed. This limitation presents a significant obstacle to LCA calculations, particularly at early design phases, where flexibility in material selection is most impactful.

To overcome this challenge, this framework proposes a structured approach to leverage average EPDs and calculate representative averages when specific data are unavailable. This approach is grounded in the principles of eco-design, which advocate for the continuous integration of LCA throughout the design phases. In phase 4, Level 2 (technical design), where detailed calculations inform material selection and optimization, the lack of specific EPDs can also be mitigated by selecting multiple generic declarations for the same material type, normalizing their data, and calculating average environmental impacts. Such practices ensure that sustainability evaluations remain robust and actionable, even when specific product data cannot be obtained.

As emphasized by Silvestre et al. [9], the adaptation of existing LCA data to national or regional contexts requires careful consideration of data quality indicators and PCRs. These criteria help practitioners identify suitable datasets while maintaining reliability and consistency across LC stages. The findings of Silvestre et al.'s [9] also underscore the importance of developing regional and sector-specific databases, which are crucial for overcoming the limitations imposed by confidentiality restrictions and inconsistent data availability.

To implement this approach effectively, the following steps are proposed.

1. **Selection of Multiple EPDs:** Choose at least three EPDs for the same material type, ensuring that they represent a diverse range of manufacturers and production processes. Geographical representativeness should be as close as possible to the construction site; if the site is in Europe, EPDs from the European context should be preferred;
2. **Normalization of Functional Units:** Align all selected EPDs to the same functional unit (e.g., converting from m^2 to m^3) to enable accurate comparisons and calculations;
3. **Calculation of Average Impacts:** Compute average values for each environmental indicator (e.g., GWP, ODP) to derive a generalized dataset representing the material's overall environmental profile;
4. **Validation of Data:** For temporal representativeness, ensure that all selected EPDs comply with standards such as ISO 14025:2006 [6] and EN 15804:2012 + A2:2019/AC:2021 [7] and align with PCRs for consistent LC analyses.

Fig. 4 further illustrates the relationships among design phases, BIM workflows, LOIN standards [19], Level(s) assessments and data management (EPDs), highlighting key milestones where optimization opportunities arise. This structured integration ensures that designers can incorporate environmental considerations into decision-making processes without overburdening workflows or delaying project timelines. By embedding LCA goals into BIM workflows, such as the BEP, and specifying sustainability objectives at each phase, project teams can systematically address environmental challenges through construction and operation from the earliest design phases.

4. Case study

In this case study, the selection and application of EPDs for wood-based materials, specifically cross-laminated timber (CLT), in the context of wall construction were explored, with the results per design phase aligned with the proposed data requirements. It validated the structured framework for EPD selection and its integration into LCA, with a focus on projects developed in Europe.

The second part of this section, the implementation of the proposed framework in a real-life case study was described through a BIM platform designed for the effective BIM–LCA integrated approach. The three types of analysis were combined, and optimization strategies for climate mitigation were used throughout the process to compare different material options and scenarios. Level 2A was combined with two material options, and the results from Level 2A were compared with those from Level 2B. The objective of this research was to test its scalability to a real-life architectural project and possible LCA environmental improvements by acting during the design phases. Ultimately, the goal was to show the numerically quantified differences between the environmental impacts with this method in the different design phases and to determine whether adding an extra LCA study in the early design phases helped optimize the building material choices and overall impacts.

4.1. Architectural introduction

The architectural case study, *Muda Reserve*, was a familiar house located in *Comporta, Grândola*, Portugal, which was provided by the promoter Vanguard Properties and constructed by Kozowood. The architectural team was from JV Studio, and the design was developed by the architect João Vieira. This case study was chosen because the architects, promoter and constructor already expressed environmental concerns and were motivated to add even more environmental improvements to their project, reducing the environmental footprint as much as possible to achieve a neutral or even negative impact.

The proposal consisted in one level that is openly connected to the landscape and dunes from *Comporta*, with five-bedroom suites, a kitchenette, an office, an exterior swimming pool and jacuzzi and an attached service area (Fig. 6). The main materials were wood and glass (Fig. 7). The architects provided the BIM modelled in Revit software from Autodesk (Figs. 6 and 7).

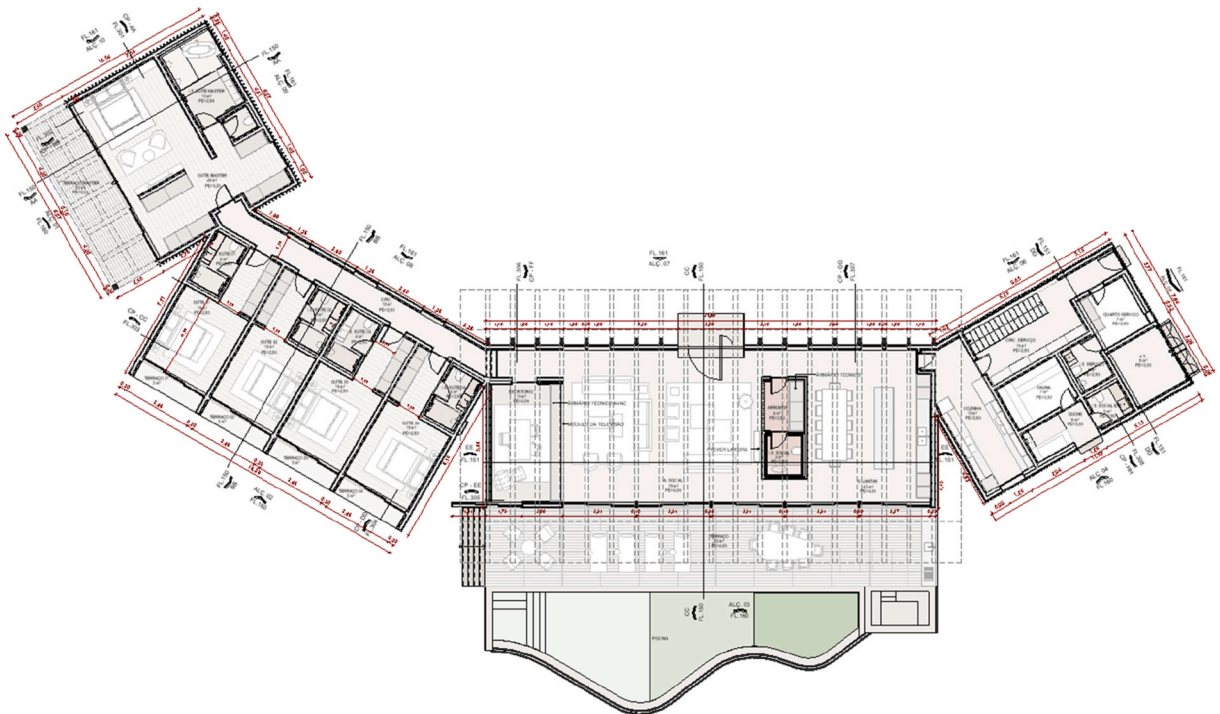


Fig. 6. Ground Floor Plan drawing of the case study.

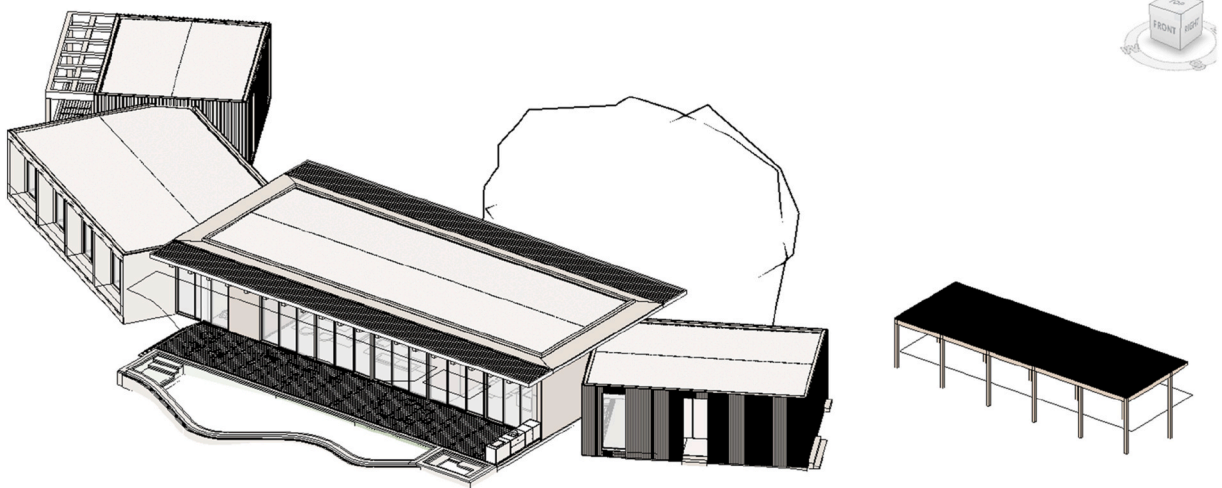


Fig. 7. Three-dimensional view of the case study.

4.2. LCA plugin overview

The three LCA evaluations across the different design phases were conducted in the Autodesk Revit software using an LCA software plugin developed in C# language and improved for this article [31–34]. This plugin had been detailed in previous publications from the same authors [31–34] but was now updated to add the functionality for an intermediate design phase (Level 2A, preliminary design). Fig. 8 represented the plugin workflow diagram, divided by the different levels of analysis, steps to access and the correspondent data. The user interface was designed by the authors to be as user-friendly as possible for non-LCA specialists, serving as a tool tailored for AEC professionals with sustainability objectives.

First, the project needed to be developed in a BIM platform. Second, the design phase of the project (Level 1, Level 2A or 2B, Fig. 10) was chosen. The third step was to select the analysis to perform.

- I LCA including the environmental indicators GWPf, GWPb, GWPl, GWPt, ADPf, ADPm, ODP, AP, WDP, POCP, PERT, and PENRT.
- II GWP including the environmental indicators GWPf, GWPl, GWPb, and GWPt.
- III Cost

Fig. 9 provided a schematic diagram of the inputs, the progress, and the expected results. Once the analysis type was selected, the environmental and/or economic indicators were converted to shared parameters that addressing all the materials and BIM objects

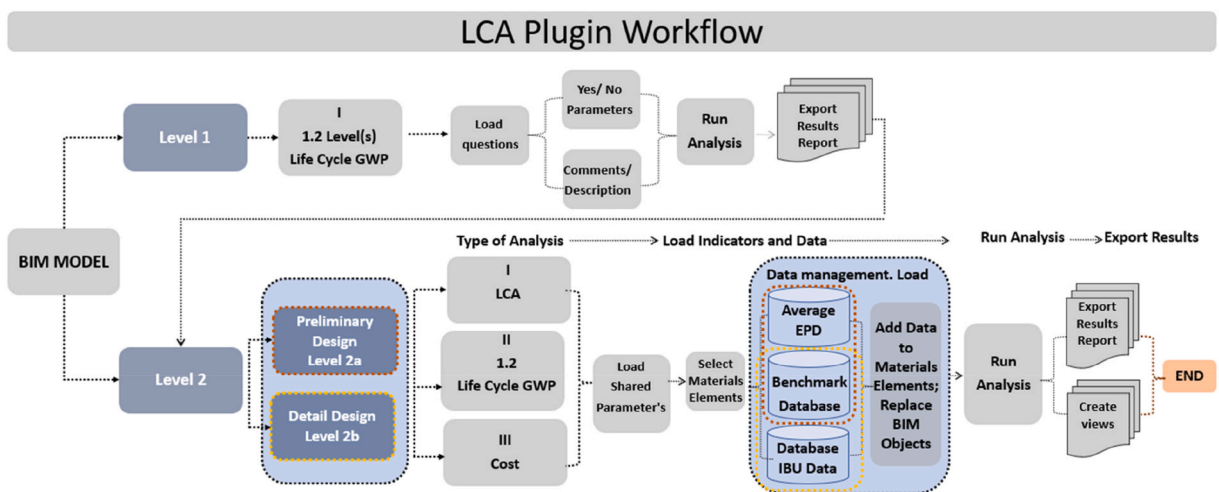


Fig. 8. LCA plugin workflow diagram: identify the intermediate levels of assessment depending on the project's design phase and the data required as inputs and outputs for each level of assessment.

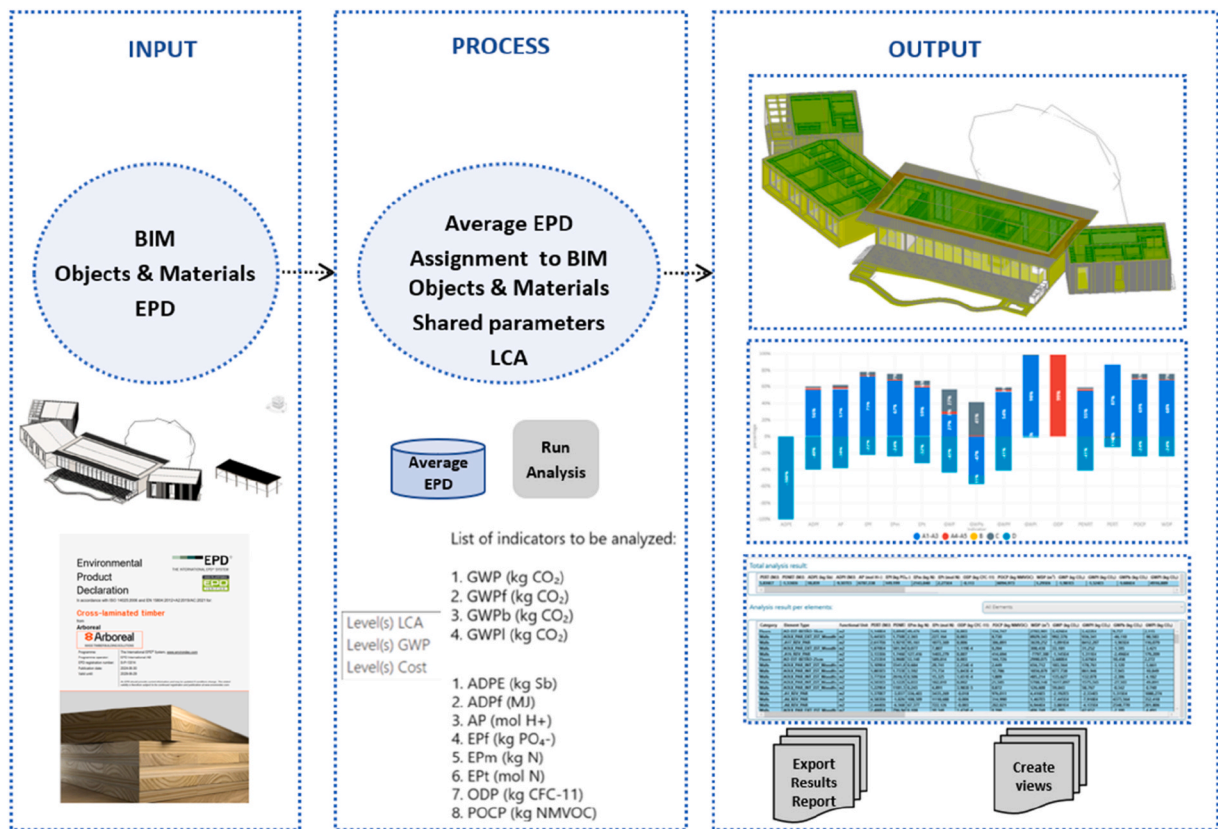


Fig. 9. Diagram of the input, process and output results of Level 2A – Average assessment.



Fig. 10. Levels of LCA per design phase of the design development: Level 1, 2A and 2B: addresses the issue of an intermediate level of assessment.

presented in the model (Fig. 11). Data correspondence was subsequently performed between the materials, BIM objects as building components, as shown in Fig. 12 (e.g., walls, floors, windows, roofs, doors, etc.), and the LCA data from the EPDs.

This study further investigated BIM-LCA interoperability, and access to data automation by connecting the tool with online databases. The automatic association of EPD data with BIM elements and materials addressed key challenges of data interoperability and

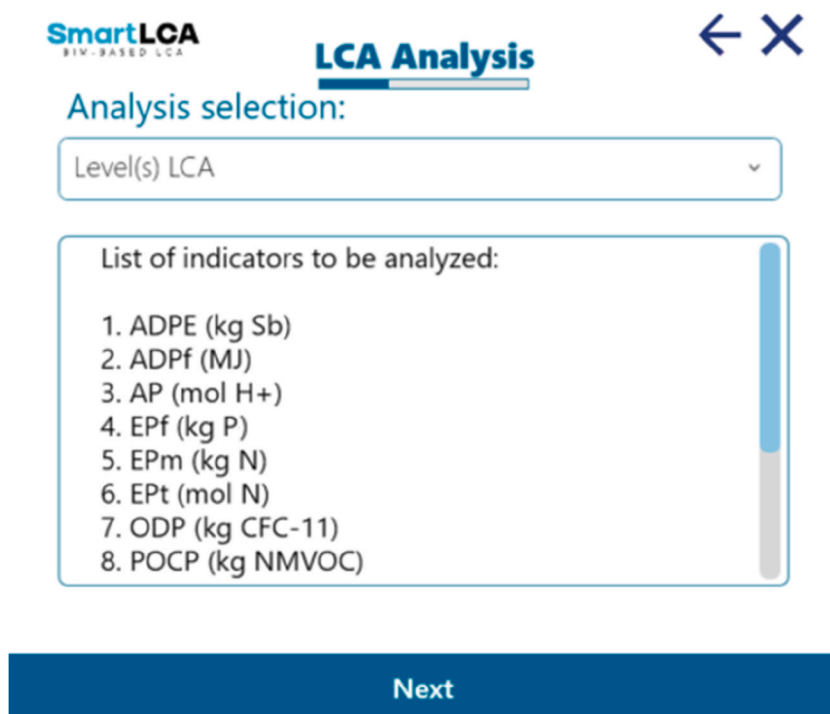


Fig. 11. Loading of the environmental indicators for the LCA study to all LC stages.

process automation. If Level 2A was chosen, the plugin opens a connection to the Eco portal and EC3 databases (Fig. 13) for EPD selection. The plugin automatically calculated the average values of the selected EPDs and assigned data to BIM components through shared parameters. For level 2B, the plugin assigned the manufacturer specific EPD via the same data bases. In both cases (Levels 2A and 2B), manual EPD entry in the shared parameters remained possible. This manual input should only be used when online EPDs were unavailable. When available, the plugin automatically populates the shared parameters with data from the selected EPDs.

The last step was to run the analysis and obtain the total analysis results, which could be exported into a schedule in Revit, an Excel file, or a 3D visualization scheme.

4.3. LCA evaluations per design phase

4.3.1. Strategic Definition—LCA level 1

The first level of analysis was aligned with the Level(s) framework promoted by the European Commission [25,26]. In their mission for Europe to become a climate-neutral continent and addressed in this investigation as “Level 1” for the preliminary design phase. In this preliminary design phase, a qualitative questionnaire addressed the environmental considerations of the project, establishing the targets, after completion it could be exported to an Excel file (Table 2). This phase highlighted the importance of setting up the premises for an efficient building, the importance of optimization in construction and its materials, the value of circularity and the design for adaptability and deconstruction. The sensitivity was assessed prior to further design development.

4.3.2. Preliminary Design—LCA level 2A study

The second phase, the Level 2A (Fig. 10), a preliminary LCA study was conducted using the average EPD method to estimate the LCA impacts in an early design phase. At this phase, the BIM model itself did not have all the layers specified or everything modelled, so this preliminary study served to help on decision-making.

4.3.2.1. Average EPD calculation. The case study highlighting that conducting a Level 2A analysis required adherence to the previously defined LOIN, which in turn leads to the development of a specific BIM model. In terms of alphanumeric information, a key challenge arose, particularly with EPDs, due to the uncertainties surrounding the exact material specification at early design phases. To address this, a framework approach was applied that enabled the use of generic EPDs. Throughout the analysis, the case study served as central validation for validating the proposed framework.

By applying the proposed framework, a structured analysis of models was provided across different project phases. This involved evaluate each phase on the basis of the available information and on the specific aspects targeted for analysis. This approach enabled a systematic assessment of how data availability and analytical objectives evolve throughout the project LC, ensuring methodological consistency and applicability.

Calculate
GWP rank

EPD Assign information to be used in the analysis

All Elements

This model has 117 elements.

Show LCA phase parameters: ☐

Over.	Category	Element Type	Functional Unit	Thickness (mm)	Area (m2)	Volume (m3)	Density (kg/m3)
N/A	Floors	AO-EST-BETÃO-18cm	m2	180	331,038	59,587	0
N/A	Walls	AOLX_PAR_EXT_EST_Woodframe Estutural_Exterior_14cm	m2	210	323,844	67,011	0
N/A	Walls	.A17_REV_PAR	m2	45	213,333	9,571	0
N/A	Walls	AOLX_PAR_EXT_EST_Woodframe Estutural_I.S.	m2	282	14,744	4,114	0
N/A	Walls	.A16_REV_PAR	m2	45	236,357	10,609	0
N/A	Floors	AO-EST-BETÃO-25cm	m2	250	355,555	88,883	0
N/A	Walls	AOLX_PAR_INT_EST_Woodframe Estutural_Interior_I.S.	m2	284	32,143	9,054	0
N/A	Walls	AOLX_PAR_INT_EST_Woodframe Estutural_Interior 8cm	m2	152	81,839	12,439	0
N/A	Walls	AOLX_PAR_INT_EST_Woodframe Estutural_Interior_14cm_P	m2	256	21,271	5,298	0
N/A	Walls	AOLX_PAR_INT_EST_Woodframe Estutural_Interior_14cm	m2	212	217,076	45,893	0

This model has 52 total materials.

Double-click a line to search Environmental Indicators for that Material

Material	Volume (m3)	Density (kg/m3)	Lifespan (year)	PERT (MJ)	PENRT (MJ)	ADPE (kg Sb)	ADPF (M)
AO-LAJE CONCRETO	59,587	2407,312	0	0	0	0	0
AO-WOODFRAME	2,432	0	0	0	0	0	0
AO-MAT-OSB	0,382	608,000	0	0	0	0	0
Air Openings	0,834	0	0	0	0	0	0
AO-MAT-PAR-MADEIRA NOGUEIRA	0,012	0	0	0	0	0	0
AO-MAT-PAR-AGEPAN	0,040	0	0	0	0	0	0
AO-MAT-PAR-TRAVERTINO ROMANO	0,163	0	0	0	0	0	0
AO-MAT-FOR-GST-2cm	0,304	1100,000	0	0	0	0	0
AO-MAT-PAR-BARRAMENTO AREIA C3002	0,058	0	0	0	0	0	0
AO-MAT-PAR-BARRAMENTO TERRACOTA KK103	0,006	0	0	0	0	0	0

Run Analysis

Element benchmark

Search EPDs

Fig. 12. BIM-LCA plugin, load of all BIM elements (blue schedule) and materials (green schedule) contained in the BIM model for LCA use.

4.3.2.2. *EPD selection criteria.* To ensure consistent and reliable LCA calculations, specific criteria were established for EPD selection, as summarized in Table 3. These criteria include the following.

1. **Material and Use Consistency:** All selected EPDs pertained to wood-based materials intended for wall construction applications, primarily CLT;
2. **Standards Compliance:** The EPDs complied with ISO 14025:2006 [6] and EN 15804:2012 + A2:2019/AC:2021 [7], ensuring adherence to internationally recognized LCA standards;
3. **Functional Unit Alignment:** EPDs used the same functional unit (e.g., 1 cubic metre). Data normalization was performed for those using different units (e.g., m² converted to m³).
4. **Programme and Validity:** EPDs were issued by credible organizations, such as the International EPD® System or *Institut Bauen und Umwelt e.V. (IBU)* and were valid for the study duration.

Table 3 lists the selected EPDs and their attributes, including the geographic location, issuing programme, and validity. Harmonizing these parameters ensured that aggregated data accurately represented the environmental impacts of wood materials in the context of LCA.

4.3.2.3. *Analysis of environmental indicators.* The environmental indicators considered for this analysis are the mandatory categories defined by EN 15804 [7], including GWPf, GWPb, GWPl, and GWPt, and additional indicators such as ODP, AP, EP, EPf, EPm, EPT, POCP, ADPm, ADPf, and WDP.

To evaluate the impact of sample size on the reliability of average values, this article compared three approaches.

1. **Three EPDs:** The preliminary analysis used the first three EPDs from Table 3, considering the data presented in detail in Table A. 1 of the attachment, and the results were shown on line “Average 3EPD” in Table 4;
2. **Five EPDs:** This approach added two more EPDs to expand the dataset (Table 3, Table A. 1), and the results wereshown on line “Average 5EPD” in Table 4;
3. **Ten EPDs:** This approach used all selected EPDs for the most comprehensive analysis (Table 3, Table A. 1), and the results were shown on the line “Average 10EPD” in Table 4.

SmartLCA
BIM-BASED LCA

Database

EPD Database information to be used in the analysis ECO PORTAL

Category - Level 1

AO-MAT-PAR-MOSAICO VERDE VTC2 Valid until (Year) Clear Search EPD

6 results found Double-click in the "URL" column to automatically open the EPD in your browser

Select	Name	Category	PERT	PENRT	ADPE	ADPf	AP
☐	CERAMIC TILES - Fior	Other transportable	46,4372	194,315	0,00176105701	-187,929	0,030554
☒	Ceramic Fine Fireclay	03 Building services	5,131541	47,86451	4,057923E-06	42,43363	0,006178
☐	Ceramic Toilet set	03 Building services	121,403424284	1200,58418132	9,9303001228E-05	1045,8007065	0,201807
☒	Ceramic cistern	03 Building services	54,279878	530,22412	5,3359488E-05	473,48712	0,091429
☒	Italian Ceramic Tiles	02 Building products	30,21471484728	209,2371816997	6,7744105464685E-0	209,0726800656	0,040691
☐	ceramic tile	02 Building products	45,18579	285,265	1,302817E-05	280,297	0,070961

BIM model materials: Show LCA phase parameters: ☐ Materials Families

Material	Volume (m3)	Density (kg/m3)	Lifespan (year)	PERT (MJ)	PENRT (MJ)	ADPE (kg St
AO-MAT-PINTURA TERR	0,180	608,000	0	8106,429	6948,114	0,003
AO-MAT-PAR-REB-2cm (	0,184	1120,000	0	8106,429	6948,114	0,003
AO-MAT-PINTURA EXTEI	0,008	1120,000	0	8106,429	6948,114	0,003
AO-MAT-IND-PED-MAR/	0,007	2407,312	0	5044,958	4,465E4	0,005
AO-MAT-PAR-MOSAICO	0,059	0	0	5044,958	4,465E4	0,005
AO-MAT-PAR-AGA-0cm	0,118	0	0	0	0	0
AO-MAT-PAR-MOSAICO	1,920E-4	0	0	0	0	0

Assign "PLEASE SELECT A RESULT" indicators to "AO-MAT-PAR-MOSAICO V..." material

Fig. 13. Connection with Eco Portal online EPD database. EPD selection for studying the average values: illustrate how to assess these average values and the data required for the assessment.

Table 2

Level 1 assessment. Report including six environmental questions, addressed or not, and how has it been incorporated into the building design concept.

Life cycle design concept	Addressed? (Yes/No)	How has it been incorporated into the building design concept?
1. Efficient building shape and form	Yes	The search for an efficient construction includes: orientation, location, and materials. Attempts are made to minimize the impact of the high summer temperatures, guaranteeing transversal ventilation in all parts of the building. Open volumes were proposed, which help the acclimatization of the house and avoid the use of mechanical ventilation.
2. Optimized NZEB construction	Yes	
3. Optimized material utilization and circular value	Yes	The grid-based design and the use of the prefabricated element construction system allow a modular dimensional optimization. This creates value for a future reuse of the material in other constructions, after dismantling.
4. Extending building and component service lives	Yes	A disassembly system provides reuse of elements after the building service life.
5. Design for adaptability	Yes	
6. Design for deconstruction	Yes	The design of the project was based on the use of a prefabricated construction system of timber structural elements, vertical props and beams. Over this structure, the interior walls are clad in plasterboard. Thus, respecting the construction profile, it is possible to have other layouts. With respect to the shape of the house, the constructive system of a concrete base and the implantation of a prefabricated structure facilitate equating to other configurations, thus reusing the original spans with little effort.
		The project design was based on the use of a prefabricated construction system of timber elements and staple plate joints on a foundation base and a partial basement in reinforced concrete. This option allows the dismantling and reuse of not only the timber structure but also the wooden planking.

The ideal scenario was to have as many data samples aligned with the requirements of the previous subsections, but there were limitations in the number of EPDs available. Some materials, such as concrete, were highly studied and have a large number of EPDs available, which was not reflected in most of the materials available on the market. This was the reason why three different numbers of

Table 3

EPD data collection and characterization to have into account when EPD is selected.

	Data held in account			Mandatory data that must be equal in different EPDs				Others	
	Name	Manufacturer	Geographical Location	Standard	Functional Unit/ Declared Unit	Product Category Rules (PCR)	Validity	Programme	URL
Wood 1 [35]	Cross-laminated timber	Arboreal	Stockholm, Sweden	ISO 14025:2006 [6] and EN 15804:2012 + A2:2019/AC:2021[7]	one cubic metre (1 m ³)	CEN standard EN 15804[7]	June 29, 2029	The International EPD® System	www.environdec.com Eco Platform
Wood 2 [36]	Solid wood panels	Nordpan	Berlin, Germany				June 27, 2028	IBU	www.environdec.com Eco Platform
Wood 3 [37]	TILLY Holzindustrie GmbH	TILLY	Berlin, Germany				June 20, 2028	IBU	Eco Platform
Wood 4 [38]	CLT	Stora Enso	Stockholm, Sweden	Oslo, Norway			October 06, 2028	The International EPD® System	www.environdec.com Eco Platform
Wood 5 [39]	CLT/Xlam panel	Essepi Srl	Stockholm, Sweden				May 30, 2029	The International EPD® System	www.environdec.com Eco Platform
Wood 6 [40]	Cross-laminated timber	Cross Timber Systems SIA	Oslo, Norway				October 10, 2027	The Norwegian EPD foundation	The Norwegian EPD foundation
Wood 7 [41]	Best wood CLT	Holzwerk Gebr. Schneider GmbH	Berlin, Germany	Hallein, Austria			April 03, 2029	The International EPD® System	www.environdec.com Eco Platform
Wood 8 [42]	Binderholz CLT	Binderholz	Hallein, Austria				September 20, 2029	The International EPD® System	Eco Platform
Wood 9 [43]	BBS SYS CLT	Bausysteme GmbH KLH	Stockholm, Sweden				June 29, 2028	The International EPD® System	www.environdec.com Eco Platform
Wood 10 [44]	Binderholz CLT BBS XL	Binderholz Bausysteme GmbH	Hallein, Austria				September 20, 2029	Stichting MRPI®	Eco Platform

Table 4

Average values from EPDs for wood materials, including 3, 5, and 10 datasets. (Refer to EPD selected in Table 3 and to the original table in attachment for detailed data Table A. 1): answers the problem of different average results depending on the size of the data sample.

Indicator	Unit	Material	A1–A3	C2	C3	C4	D
GWP-fossil	kg CO ₂ eq.	Average 3EPD	1.22E+02	1.23E + 00	1.16E + 01	0.00E + 00	–3.62E + 02
		Average 5EPD	1.10E + 02	3.30E + 00	1.10E + 01	0.00E + 00	–2.19E + 02
		Average 10EPD	1.19E + 02	1.42E + 01	1.09E + 01	7.08E-02	–1.60E + 02
GWP-biogenic	kg CO ₂ eq.	Average 3EPD	–8.14E + 02	2.17E-02	5.31E + 02	2.86E + 02	–9.62E + 00
		Average 5EPD	–8.01E + 02	1.44E-02	6.32E + 02	1.72E + 02	–1.37E + 02
		Average 10EPD	–7.39E + 02	1.02E-02	6.71E + 02	9.44E + 01	–7.05E + 01
GWP-luluc	kg CO ₂ eq.	Average 3EPD	1.17E + 00	1.56E-02	2.68E-02	0.00E + 00	–4.15E-02
		Average 5EPD	1.06E + 00	1.02E-02	1.65E-02	0.00E + 00	–8.05E-02
		Average 10EPD	1.19E + 00	5.98E-03	8.89E-03	2.38E-05	–1.67E-01
GWP-total	kg CO ₂ eq.	Average 3EPD	–6.91E + 02	1.27E + 00	5.42E + 02	2.86E + 02	–3.72E + 02
		Average 5EPD	–5.56E + 02	1.17E + 00	4.82E + 02	1.72E + 02	–2.77E + 02
		Average 10EPD	–6.39E + 02	1.42E + 01	6.02E + 02	9.45E + 01	–2.83E + 02
ODP	kg CFC 11 eq.	Average 3EPD	1.69E-06	9.33E-09	1.29E-07	0.00E + 00	–2.45E-06
		Average 5EPD	1.15E-02	3.44E-03	6.46E-03	7.28E-08	–7.19E-06
		Average 10EPD	5.76E-03	1.72E-03	3.23E-03	5.53E-08	–9.06E-06
AP	mol H + eq.	Average 3EPD	7.76E + 00	4.49E-03	5.22E-02	0.00E + 00	1.52E-01
		Average 5EPD	4.72E + 00	4.03E-03	7.23E-02	1.63E-09	–5.72E-02
		Average 10EPD	2.65E + 00	6.70E-02	8.18E-02	6.00E-04	–2.90E-01
EP-freshwater	kg P eq.	Average 3EPD	2.26E-02	2.86E-05	1.69E-03	0.00E + 00	–2.08E-03
		Average 5EPD	2.04E-02	2.18E-03	1.03E-03	0.00E + 00	–1.13E-02
		Average 10EPD	2.18E-02	1.17E-03	1.07E-03	2.90E-05	–3.38E-02
EP-marine	kg N eq.	Average 3EPD	3.03E-01	2.00E-03	1.73E-02	0.00E + 00	2.34E-02
		Average 5EPD	2.61E-01	2.51E-02	2.92E-02	0.00E + 00	–8.18E-02
		Average 10EPD	2.25E-01	3.84E-02	3.70E-02	1.58E-03	–1.05E-01
EP-terrestrial	mol N eq.	Average 3EPD	2.54E + 00	2.14E-02	1.85E-01	0.00E + 00	3.03E-01
		Average 5EPD	1.76E + 00	2.62E-02	3.25E-01	0.00E + 00	–1.00E-01
		Average 10EPD	2.16E + 00	2.95E-01	4.05E-01	2.42E-03	–7.93E-01
POCP	kg NMVOC eq.	Average 3EPD	1.04E + 00	4.71E-03	5.95E-02	0.00E + 00	1.62E-02
		Average 5EPD	7.17E-01	4.08E-03	9.21E-02	5.70E-13	–6.83E-02
		Average 10EPD	7.29E-01	1.00E-01	1.08E-01	9.60E-04	–2.21E-01
ADP minerals & metals	kg Sb eq.	Average 3EPD	2.50E-04	9.37E-07	2.54E-05	0.00E + 00	–8.96E-05
		Average 5EPD	2.09E-04	8.42E-06	1.93E-05	0.00E + 00	–8.38E-05
		Average 10EPD	5.49E-04	4.81E-05	1.64E-05	5.29E-07	–1.63E-04
ADP-fossil	MJ	Average 3EPD	1.93E + 03	1.67E + 01	1.72E + 02	0.00E + 00	–6.06E + 03
		Average 5EPD	1.34E + 03	1.91E + 01	1.27E + 02	0.00E + 00	–4.65E + 03
		Average 10EPD	1.66E + 03	1.86E + 02	9.78E + 01	1.40E + 00	–3.28E + 03
WDP	m ³	Average 3EPD	1.93E + 01	6.05E-02	1.44E + 00	0.00E + 00	–1.86E + 01
		Average 5EPD	1.60E + 01	8.71E-02	1.22E + 00	1.02E-06	–1.67E + 01
		Average 10EPD	3.49E + 02	1.71E-01	8.50E + 00	5.03E-02	–1.58E + 01

EPDs (3, 5 or 10) were chosen as the average values. The metric considered the existence of at least 3 EPDs for each material of the building component for global building LCA results. This metric was studied in a case study, which is subsequently described in this section.

Figs. 14 and 15 provided a visualization of the results, highlighting trends and variations in environmental impacts across different sample sizes.

- Fig. 14 presents the GWPf, GWPb, GWPl, and GWPt results; increasing the sample size reduced variability and enhanced confidence in average values.
- Fig. 15 focused on other environmental indicators, such as ODP, AP, EP, POCP, and WDP. Significant variability was observed in certain indicators, particularly the ODP and WDP. These findings suggested that, for indicators with high variability, such as WDP, average values may not be appropriate during intermediate design phases. Instead, these indicators should be evaluated at later phases when specific material choices are finalized.

This investigation additionally revealed that increasing the sample size reduced the variability in most indicators, which aligns with prior findings on data reliability in LCA studies [9,31–34]. In conclusion, increasing sample size reduced variability, consistent with findings in previous LCA literature. Figs. 14 and 15 showed these differences. Indicators with high variability (especially WDP and ODP) were found unsuitable for early-phase averaging. The data in Figs. 14 and 15 are from Table A. 1 in the attachment.

4.3.2.4. Practical Implications. This case study presented key recommendations for practitioners and contributed to the implementation of the EPBD [24] in European countries.

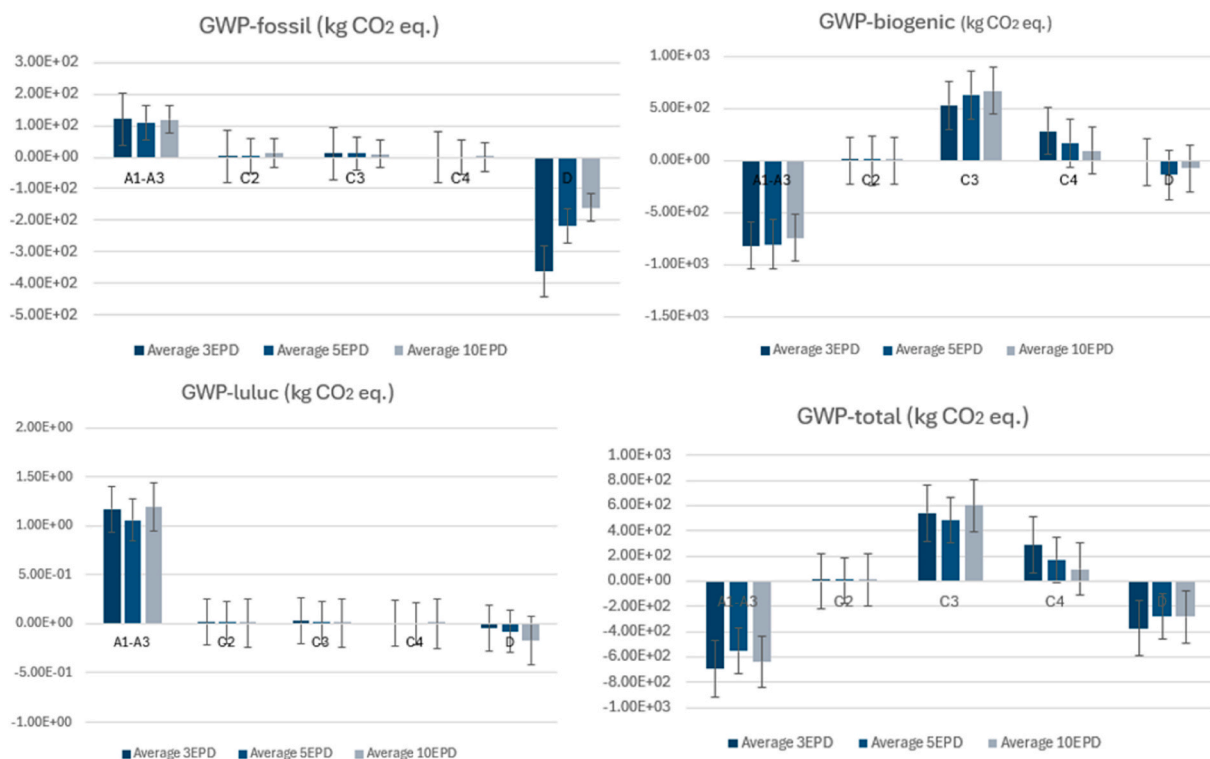


Fig. 14. Environmental indicators GWPf, GWPb, GWPl, and GWPt: Average values based on 3, 5 and 10 EPDs to answer the problem of different average results depending on the size of the data sample (Refer to EPD selected in [Table 3](#), [Table 4](#) for average data, and to the original table in attachment for detailed data [Table A. 1](#)).

- 1. Use of Average EPD Data:** At early design phases, in public procurement, or in cases where specific EPDs were unavailable, practitioners should calculate averages using at least three EPDs of the same material type, ensuring alignment in functional units and standards;
- 2. Tailored Transportation Analysis:** For projects where transportation impacts were significant, detailed B4 calculations should be integrated into LCA workflows, considering transport distance, mode, and energy use [7];
- 3. Indicator-Specific Approaches:** For indicators with high variability, such as WDP, decisions should be deferred until specific materials are chosen at later design phases, ensuring more accurate sustainability assessments.

4.3.2.5. Preliminary conclusions and findings from the average EPD method. The findings of the proposed average EPD framework for EPD selection and LCA integration, particularly at early design phases, were presented. By addressing data consistency, sample size impacts, and transportation considerations, this research demonstrated a scalable and adaptable approach for integrating EPD data into LCA workflows. These results supported the broader application of this framework in diverse project contexts, ensuring reliable and actionable sustainability assessments. The environmental indicators considered for this analysis were the mandatory impact categories according to EN 15804 [7]. For example, in the case of a wood element and considered ten different EPDs, named here as woods 1 to 10, the total average values for three exercises were achieved: first, the results by three datasets (woods 1, 2 and 3); second, the results by five datasets (woods 1, 2, 3, 4 and 5); and third, an exercise that used 10 datasets (woods 1, 2, 3, 4, 5, 6, 7, 8, 9, 10). For each of the LCA indicators listed above, the corresponding results were shown in [Tables 4](#) and in the charts in [Figs. 14 and 15](#).

[Table 5](#) showed a comparison of the results between the proposed framework at early design phases using an average of 10 datasets and the detail design where wood 6 was chosen. [Fig. 16](#), a graphical representation used the data from [Table 5](#), which was the result of the proposed method per design phase (preliminary design—average EPD (average of 10 EPDs) and detail design—specific EPD) according to the LOIN from [Table 1](#) and the proposed level of environmental data aligned with the proposed BIM requirements per design phase. The findings indicated that data granularity changes for different LC stages that use generic data at the preliminary phases not only contribute favourably to a preliminary LCA study but also contribute to environmental optimization at the detailed design and construction phases. Additionally, the impact of the material choices should be actively mitigated early in the design phases when changes can be made and should progress to the detailed design and construction phases according to the specific EPDs to ensure accurate LCA studies of the environmental impacts. In conclusion, [Table 5](#) and [Fig. 16](#) showed the comparison between early-phase averages and detailed design using a specific EPD. The results indicated that generic data in preliminary phases supported decision-making and improved environmental optimization.

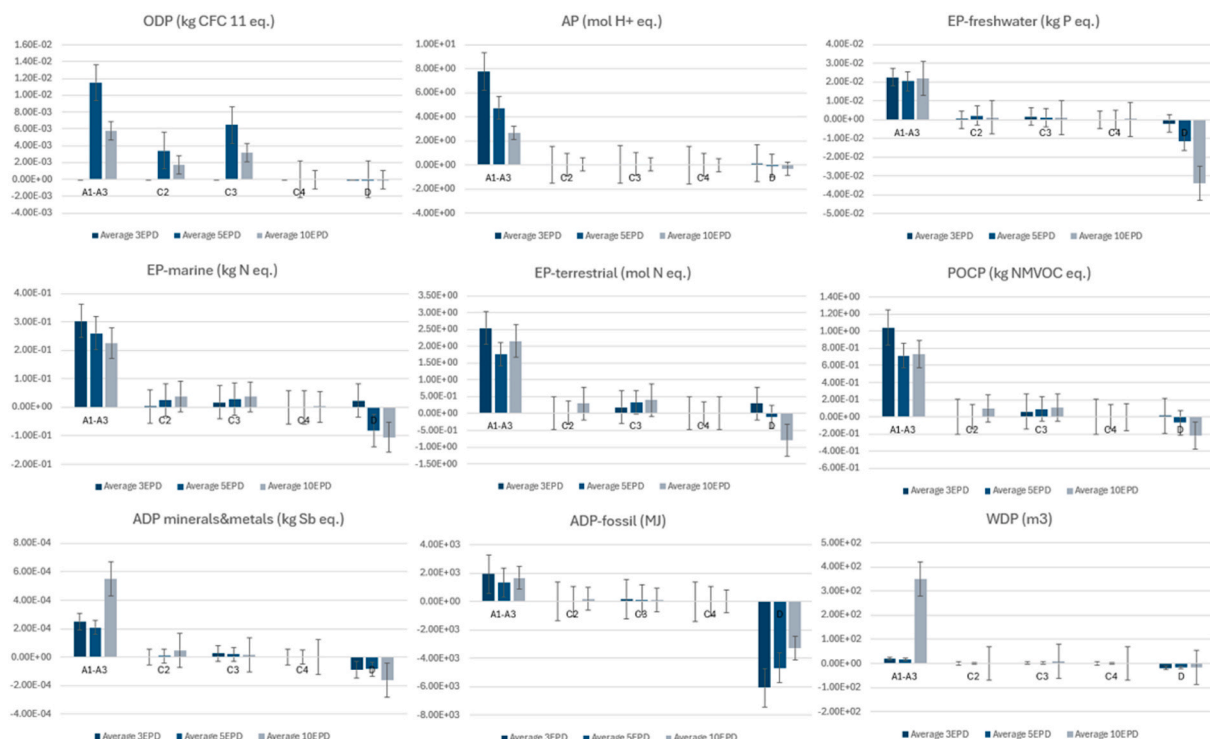


Fig. 15. Environmental indicators ODP, AP, EPf, EPm, Ept, POCP, ADPm, ADPf, and WDP: Average values based on 3, 5 and 10 EPDs to answer the problem of different average results depending on the size of the data sample (Refer to EPD selected in Table 3, Table 4 for average data, and to the original table in attachment for detailed data Table A. 1).

4.3.2.6. Preliminary Design—LCA Level 2A study. An overall LCA of a building was conducted with two different material options, CLT and wood frame (WF), and the different impacts were presented in a table prior to the architect's decision.

The objective was to estimate the impacts per material choice (e.g., CLT versus wood frame) rather than per manufacturer. Five EPDs were selected (Fig. 13, first column). The calculation of the average EPD of the LCA impacts (Fig. 17) were assigned to the properties of the material on the BIM element (wall, floor, and roof), enabling the first LCA estimation for Level 2A (preliminary design) (Figs. 13 and 17).

Fig. 18 presented the quantity tables of all BIM elements and materials presented in the model per category with the average EPD of the environmental impacts addressed.

As an intermediate step in the Level 2A phase, the model was studied by replacing the core material wood in the first option with CLT, and in the second option with WF, the method of average data was performed for both options, and the results were compared, aiming for an optimized solution in an intermediate phase to aid in decision-making. The last step of this preliminary phase of the LCA study was to run the analysis, perform the LCA calculations and obtain the Level 2A results (Fig. 19).

Table 6 presented the total results by comparing Option 1 CLT with Option 2 WF and contained data extracted from the BIM model. With the overall results, the architects had two different materials with two different environmental results and can choose the optimized solution. As shown in Table 6, CLT had a lower environmental impact on most of the indicators, including GWPt. The results were visualized with a colour scheme that depicts the impacts from green, the lowest impact, to red, the highest impact, progressively transitioning to intermediate colours such as yellow (Fig. 20, Fig. 21). Fig. 20 showed the 3-dimensional (3D) results obtained using CLT, and Fig. 21 shows the results obtained using WF for the total analysis results for GWP in LCA stages A1–A3. This is a visual approach for designers and non-LCA specialists to visually and rapidly understand the results.

In conclusion, in this intermediate study, the preferred solution was Option 1 CLT for advancing to the next phase.

The total analysis results of this phase were expressed in the results table, (Fig. 19), stacked column charts per LCA stage (Fig. 22), pie charts, three-dimensional views (Fig. 20), a schedule in Revit, and exported to an Excel file.

4.3.2.7. Detail Design—LCA Level 2B study. The intermediate phase provided the architects with a notion of the environmental impacts and the opportunity to optimize the model with different material options prior to a detailed phase of execution/preconstruction. The third phase of the assessment represents the detail design project phase and corresponds with the LCA Level 2B study. At this phase, the model had a higher level of detail, and most of the decisions were already made and a final LCA study is performed.

The plugin had the environmental indicators filled with average data, and these data needed to be replaced by the chosen EPD for final decisions on materials and elements, enabling a final LCA study. For the detail design phase when opening the plugin, Level 2B

Table 5

Results of the proposed method per design phase (preliminary design and detail design) to illustrate the evolution of the results along the design phase process.

Indicator	Unit	Design Phase	Material	A1-A3	C2	C3	C4	D
GWP-fossil	kg CO ₂ eq.	Preliminary Design	Average of 10EPD	1.19E + 02	1.42E + 01	1.09E + 01	7.08E-02	-1.60E + 02
		Detail Design	Chosen Wood 6	1.93E + 02	8.60E + 01	4.80E + 00	1.60E-01	-1.70E + 02
GWP-biogenic	kg CO ₂ eq.	Preliminary Design	Average of 10EPD	-7.39E + 02	1.02E-02	6.71E + 02	9.44E + 01	-7.05E + 01
		Detail Design	Chosen Wood 6	-1.10E + 03	2.30E-02	6.30E + 02	5.90E + 00	-1.80E + 01
GWP-luluc	kg CO ₂ eq.	Preliminary Design	Average of 10EPD	1.19E + 00	5.98E-03	8.89E-03	2.38E-05	-1.67E-01
		Detail Design	Chosen Wood 6	1.37E + 00	1.60E-03	5.80E-04	3.90E-06	-3.30E-01
GWP-total	kg CO ₂ eq.	Preliminary Design	Average of 10EPD	-6.39E + 02	1.42E + 01	6.02E + 02	9.45E + 01	-2.83E + 02
		Detail Design	Chosen Wood 6	-9.04E + 02	8.60E + 01	6.40E + 02	6.50E + 00	-1.90E + 02
ODP	kg CFC 11 eq.	Preliminary Design	Average of 10EPD	5.76E-03	1.72E-03	3.23E-03	5.53E-08	-9.06E-06
		Detail Design	Chosen Wood 6	3.17E-05	1.90E-05	2.90E-07	3.50E-08	-8.40E-06
AP	mol H + eq.	Preliminary Design	Average of 10EPD	2.65E + 00	6.70E-02	8.18E-02	6.00E-04	-2.90E-01
		Detail Design	Chosen Wood 6	1.20E + 00	5.40E-01	6.30E-02	1.70E-03	-9.70E-01
EP-freshwater	kg P eq.	Preliminary Design	Average of 10EPD	2.18E-02	1.17E-03	1.07E-03	2.90E-05	-3.38E-02
		Detail Design	Chosen Wood 6	5.11E-02	3.30E-04	2.40E-03	2.80E-04	-1.70E-01
EP-marine	kg N eq.	Preliminary Design	Average of 10EPD	2.25E-01	3.84E-02	3.70E-02	1.58E-03	-1.05E-01
		Detail Design	Chosen Wood 6	3.43E-01	2.20E-01	3.50E-02	1.30E-02	-1.90E-01
EP-terrestrial	mol N eq.	Preliminary Design	Average of 10EPD	2.16E + 00	2.95E-01	4.05E-01	2.42E-03	-7.93E-01
		Detail Design	Chosen Wood 6	3.49E + 00	2.40E + 00	3.40E-01	8.30E-03	-1.70E + 00
POCP	kg NMVOC eq.	Preliminary Design	Average of 10EPD	7.29E-01	1.00E-01	1.08E-01	9.60E-04	-2.21E-01
		Detail Design	Chosen Wood 6	1.25E + 00	8.60E-01	8.00E-02	3.90E-03	-5.00E-01
ADP minerals & metals	kg Sb eq.	Preliminary Design	Average of 10EPD	5.49E-04	4.81E-05	1.64E-05	5.29E-07	-1.63E-04
		Detail Design	Chosen Wood 6	2.12E-04	3.60E-06	2.50E-06	8.10E-09	-1.10E-05
ADP-fossil	MJ	Preliminary Design	Average of 10EPD	1.66E + 03	1.86E + 02	9.78E + 01	1.40E + 00	-3.28E + 03
		Detail Design	Chosen Wood 6	3.30E + 03	1.20E + 03	3.70E + 01	2.20E + 00	-3.60E + 03
WDP	m ³	Preliminary Design	Average of 10EPD	3.49E + 02	1.71E-01	8.50E + 00	5.03E-02	-1.58E + 01
		Detail Design	Chosen Wood 6	4.62E + 01	1.20E-01	-5.50E + 00	5.50E-04	-4.00E + 01

should be selected (Fig. 10), and then the environmental parameters for the analysis should be confirmed (Fig. 11). All the materials and BIM objects were loaded into the plugin (Fig. 12).

The next step was to open the EPD database and replace the average data with the final decision on materials and elements in the detail design for construction (specific manufacturer EPD). The plugin opens the database (Fig. 13), the final EPD was selected, and it was assigned to the material (Fig. 23).

Fig. 24 represented the final decision on BIM objects and materials EPD assessment. With the data assignment completed, the designer can now obtain the LCA results. Fig. 26 showed a graphical representation of the percentage of impacts per environmental indicator per LCA stage.

The LCA impacts of each environmental indicator remained in the BIM objects, each respective material as per Fig. 27, and each of the indicators were converted into a shared parameter and remained as a property even after the plugin was closed.

5. Discussion of results: comparison of the evaluations for the preliminary Design—LCA Level 2A and detail Design—Level 2B

In terms of the purpose-driven information requirements, the alignment between LOIN and LCA was determined by dividing the requirements according to different design phases. This included the development of the BIM model, the preliminary analysis that enabled optimized and conscientious decisions during the design phases. The most effective timing for testing different solutions (CLT vs. WF) occurred at Level 2A, where the choices may be optimized. Regarding the Level 2B, both the project and the models were too

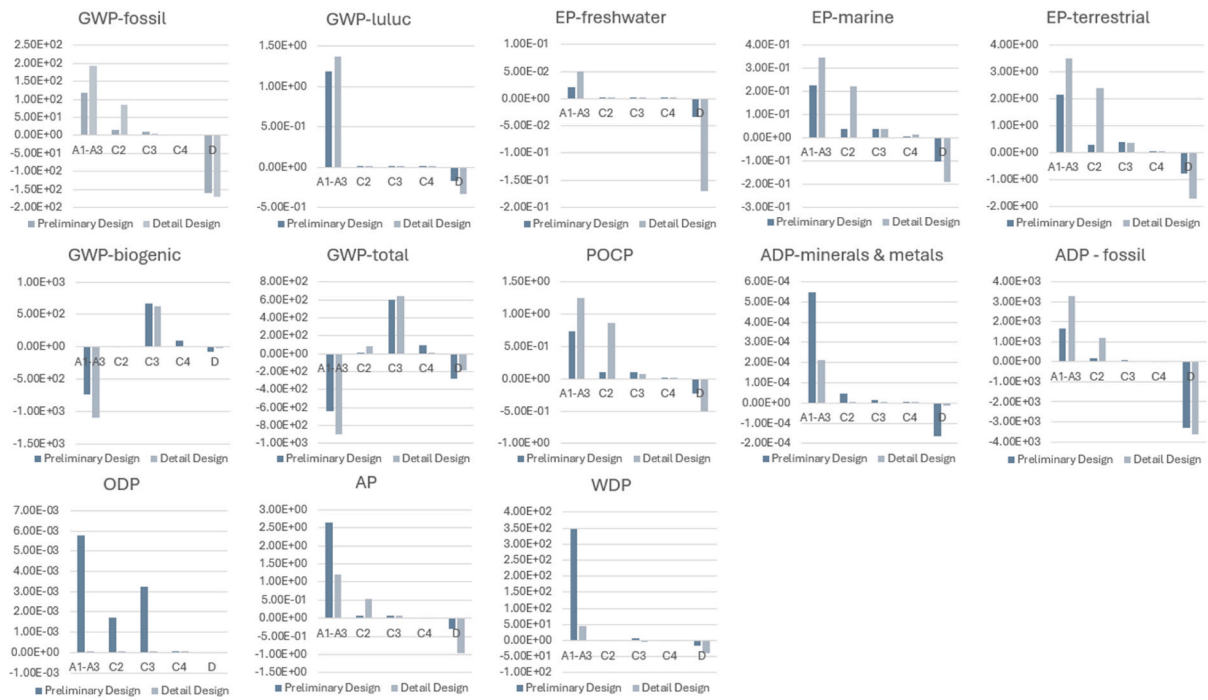


Fig. 16. Results of the proposed method per design phase (preliminary design—average EPD (average of 10 EPDs) and detail design—specific EPD) according to the LOIN from Table 1 and data from Table 4: illustrate of the evolution of the results along the design phase process.

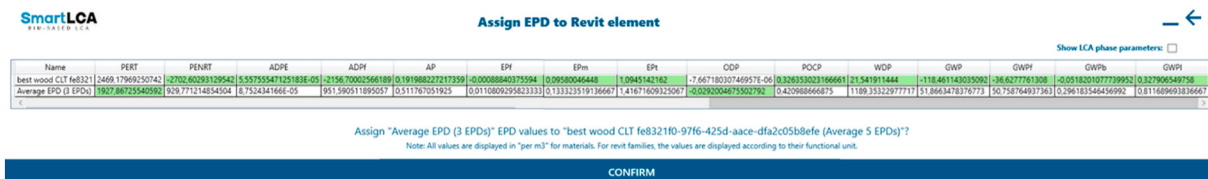


Fig. 17. Assignment of the average EPD to a material. Addressing the issue of assigning data to BIM materials and objects. With the quantified numerical visualization of each environmental indicator, comparison of EPD replacement.

developed for substantial alterations to remain feasible, and only minor adjustments to finishes are typically possible. In that sense, the findings reinforce that meaningful environmental optimization must occur during earlier design phases, when flexibility is highest.

Table 7 shows the final comparison of the results between Level 2A (average method), and Level 2B (specific EPD). After the preliminary optimization, when the final EPDs were selected, the total analysis results per indicator improved the performance and reduced the environmental impact.

The case study began with the evaluation of two material options. The second phase involved assessing the stability of the proposed framework through a real-world case study of a residential plot.

The framework is designed to be adaptable to both residential and office buildings. It demonstrates the potential for global application of the purpose driven design framework, especially in large-scale infrastructure projects where cumulative environmental gains scale substantially across extended construction networks. The purpose-driven approach may be seen not just as a support mechanism, but as a strategic enabler of sustainable design at scale. The framework is therefore positioned as suitable for a range of project types, including buildings and infrastructure providing particularly valuable for competitive proposals in both private and public procurement settings.

- Barriers to Implementation and Digital Maturity

The next step will be to test the framework on a larger-scale project and explore its applicability to various building types. The authors anticipate no significant challenges in scaling up the project, for different contexts. As the critical factor lies in the accurate detailing of material choices and their integration with the BIM model in a rigorous manner. One of the main advantages of BIM is the ability to address a large amount of data.

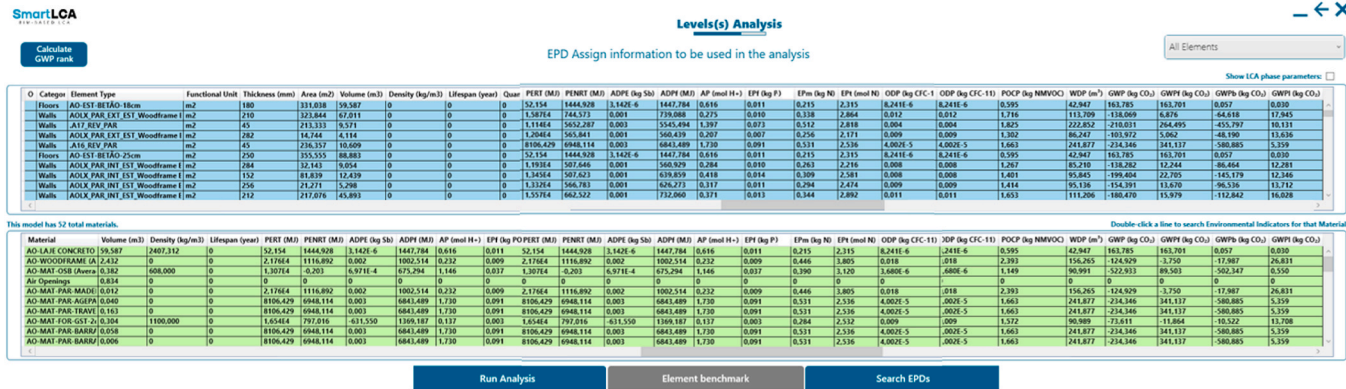


Fig. 18. Average EPD addressed to BIM elements and construction materials in the model: shows data assignment to BIM materials and objects.

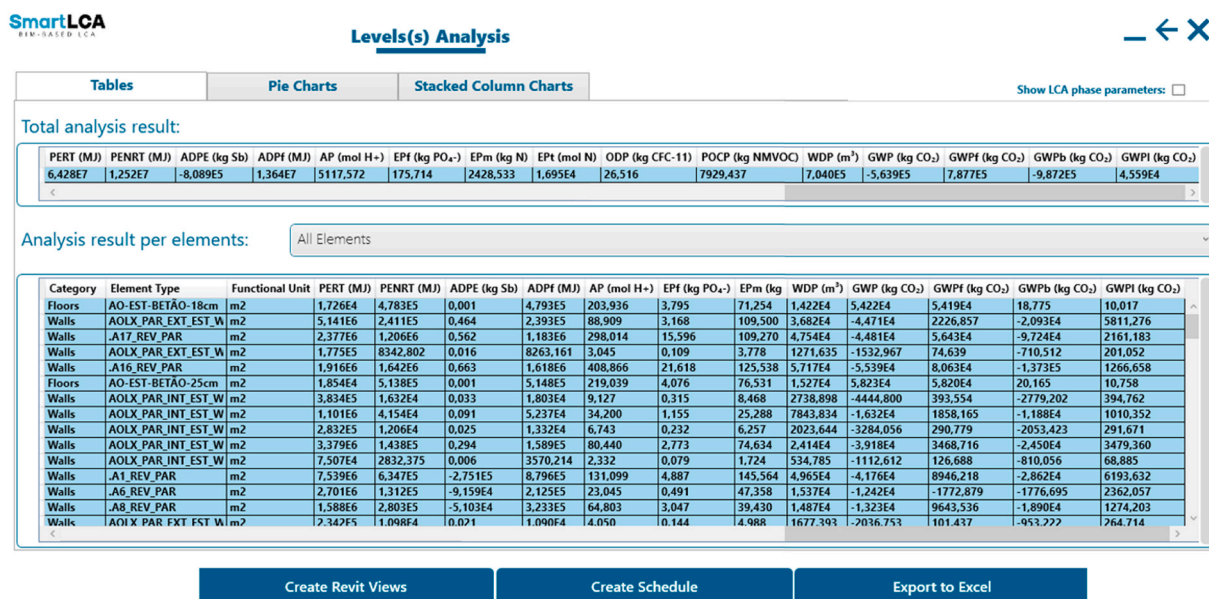


Fig. 19. Preliminary design with Level 2A total analysis results: shows global project results (schedule above), data assignment to BIM materials and objects (schedule below).

Regarding policymakers, in the integration of the proposed framework in public procurements some barriers may arise regarding the twin transition and the technological implementation. Both BIM-LCA workflow demand additional training and capacity-building for policymakers to evaluate environmental performance criteria and manage data-driven procurement processes effectively.

Furthermore, in regions with low levels of digital maturity, barriers such as limited digital infrastructure, insufficient computational capacity, and fragmented data standards may hinder the adoption of BIM-LCA workflows. These constraints can delay the transition toward data-integrated environmental decision-making and create disparities in implementation between regions.

- Stakeholder Training and Practical Implications

To facilitate widespread adoption of the proposed framework, targeted training programs are essential for designers, contractors, policymakers, and procurement officers. Designers and contractors require practical instruction on modelling requirements, LOIN alignment, and accurate assignment of EPDs to BIM objects. Policymakers and procurement officers, on the other hand, require training in data interpretation, environmental indicator verification, and the use of average EPDs during early-phase procurement decisions, particularly when specific manufacturer products cannot yet be selected.

By clarifying the training needs for each stakeholder group, this study highlights the practical steps required to enable consistent and scalable BIM-LCA integration across design phases.

From a training perspective, coordinated upskilling is essential. Designers, engineers, contractors, and procurement officers require targeted training in BIM, modelling, standards, the importance of the information, LOIN structuring, interoperability, LCA, and EPD evaluation to ensure consistent and reliable BIM-LCA implementation. The requested skills are different depending on the function of the person within the AEC ecosystem. Policymakers had to know to use projects BIM-LCA information and data, for that it is necessary training in BIM, LCA, management. For designers must have software training specific both BIM and LCA.

- Digital Transformation and Standardization

Overall, the findings contribute to demystifying BIM-LCA integration and supporting the broader digital transformation of the construction sector, particularly through standardization and purpose-driven information delivery across design phases. Serving as a call for action for both private and public sectors recommending the adoption of purpose driven design framework, while also emphasizing the relevance of intermediate assessment levels using average EPDs during design phases.

Concerning the scalability, as the complexity and size of a BIM project increase. More powerful hardware is required to ensure smooth performance and efficient model handling. This is directly reflected in the cost of the hardware itself that should be acknowledge in digital transitions cost proposals. At least, data limitations may arise at Level 2B. Being product-specific, EPDs may not be available at the regional or even national level. In such cases, it is recommended to use similar EPDs available on international markets. This limitation should be acknowledged in the final LCA report. To avoid compromising the quality of the final assessment, this situation should affect no more than 10 % of the specified project materials. It is also recommended that designers first contact manufacturers to raise awareness about the need for EPDs and their associated environmental benefits. Additionally, some

Table 6

Level 2A total LCA results: comparison results of Option 1 CLT versus Option 2 WF materials to illustrate the comparison of results using two material options.

Average method—Level 2A													
LCA Stage		Total		A1–A3		A4–A5		B		C		D	
Environmental Indicators	Functional Unit	Total CLT	Total - WF	CLT	WF	CLT	WF	CLT	WF	CLT	WF	CLT	WF
GWPf	kg CO ₂ eq.	7,88E+05	1,26E+06	2,40E+06	2,11E+06	9,16E+04	1,34E+05	2,33E+02	2,57E+04	1,33E+05	1,54E+05	−1,84E+06	−1,16E+06
GWPb	kg CO ₂ eq.	−9,87E+05	−1,45E+06	−2,97E+06	−2,68E+06	4,62E+04	7,30E+04	3,84E+00	9,63E+01	2,63E+06	2,08E+06	−6,99E+05	−9,18E+05
GWPl	kg CO ₂ eq.	4,56E+04	1,65E+04	4,59E+04	1,97E+04	1,04E+02	9,42E+01	9,02E-01	5,19E+02	2,61E+02	3,16E+02	−6,57E+02	−4,12E+03
GWPt	kg CO ₂ eq.	−5,64E+05	−2,14E+05	1,28E+06	1,08E+06	1,28E+05	1,95E+05	2,38E+02	2,58E+04	1,27E+06	1,07E+06	−1,98E+06	−8,31E+05
ADPf	MJ	1,36E+07	2,36E+07	3,78E+07	3,39E+07	1,22E+06	1,79E+06	4,68E+03	3,46E+05	1,57E+06	1,89E+06	−2,69E+07	−1,43E+07
ADPm/ADPE	kg Sb eq.	−8,09E+05	1,42E+01	7,17E+00	1,17E+01	2,97E-01	8,45E-01	2,00E-03	2,03E-01	1,36E-01	1,33E+00	−8,09E+05	4,60E-02
AP	mol H+ eq.	5,12E+03	8,74E+03	1,24E+04	1,35E+04	3,34E+02	7,71E+02	1,83E+00	1,16E+02	7,25E+02	8,89E+02	−8,34E+03	−6,58E+03
EPf	kg P eq.	1,76E+02	2,75E+02	2,30E+02	4,12E+02	2,41E+00	1,14E+01	5,20E-02	6,73E+00	1,37E+01	3,08E+01	−7,02E+01	−1,85E+02
EPm	kg N eq.	2,43E+03	2,86E+03	3,13E+03	2,96E+03	1,04E+02	2,18E+02	3,50E-01	2,56E+01	3,26E+02	3,40E+02	−1,13E+03	−6,85E+02
EPt	mol N eq.	1,70E+04	2,19E+04	2,77E+04	2,94E+04	1,11E+03	2,37E+03	3,08E+00	1,67E+02	2,99E+03	3,35E+03	−1,48E+04	−1,34E+04
ODP	kg CFC-11 eq.	2,65E+01	−3,33E+01	1,04E-01	1,58E-01	2,65E+01	5,53E+00	1,71E-05	3,00E-03	8,00E-03	1,00E-02	−1,33E-01	−3,90E+01
POCP	kg NMVOC eq.	7,93E+03	8,60E+03	1,04E+04	9,95E+03	2,85E+02	7,22E+02	9,62E-01	6,36E+01	7,98E+02	1,02E+03	−3,58E+03	−3,16E+03
WDP	m ³ world eq. deprived	7,04E+05	2,70E+06	9,38E+05	3,28E+06	1,01E+04	2,45E+04	1,25E+03	1,54E+05	9,17E+04	7,02E+04	−3,37E+05	−8,22E+05
PERT	MJ	6,43E+07	5,56E+07	7,55E+07	6,58E+07	4,20E+04	9,36E+04	2,87E+02	2,14E+04	−1,82E+06	3,84E+06	−9,41E+06	−1,42E+07
PENRT	MJ	1,25E+07	2,45E+07	3,87E+07	3,52E+07	1,24E+06	1,87E+06	5,39E+03	4,21E+05	1,58E+06	1,93E+06	−2,90E+07	−1,49E+07

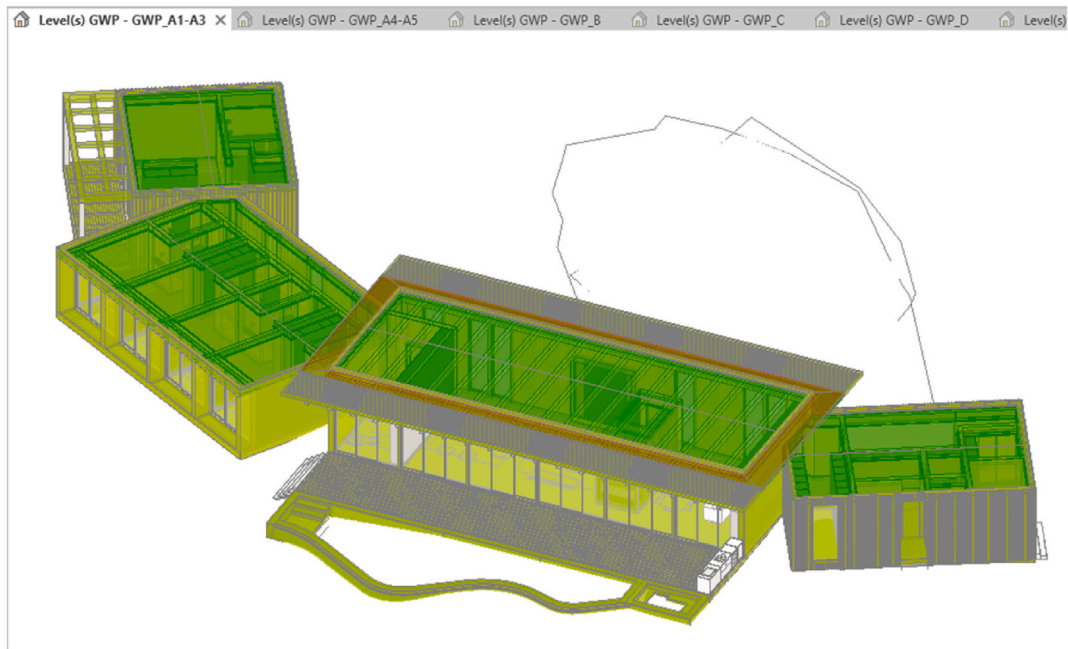


Fig. 20. Preliminary design with Level 2A total analysis result: three-dimensional view of GWP A1–A3 impacts for Option 1 CLT to provide a graphical visualization of LCA results for non-specialists.

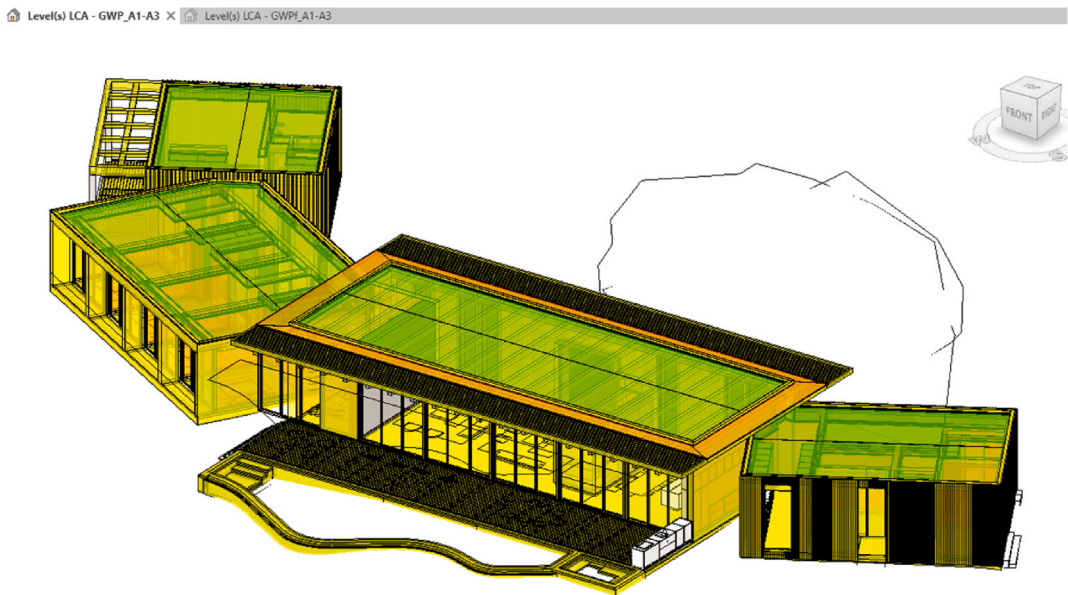


Fig. 21. Preliminary design with Level 2A total analysis results: three-dimensional view of GWP A1–A3 impacts for Option 2 WF to provide a graphical visualization of LCA results for non-specialists.

manufacturers provide EPDs only upon request, further justifying early engagement, prior to a specific decision. In conclusion, selecting materials with available EPDs is more suitable for conducting robust and reliable LCA.

6. Conclusion & recommendations for future research

The comprehensive integration of BIM across design phases, testing the impact of different material solutions to achieve optimized outcomes and purpose-driven information requirements, and the consideration of LOIN present a transformative approach to project development, data management, and LC management.

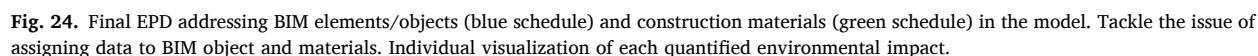
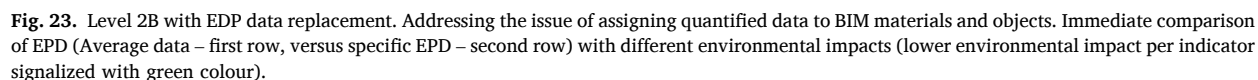
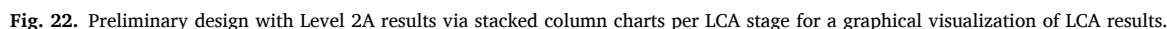


Table 7

Total LCA results: Level 2A (preliminary design) and Level 2B (detail design) to illustrate the evolution of the results along the design phase process.

Design Phase		Level 2A PD	Level 2B DD	Level 2A PD	Level 2B DD	Level 2A PD	Level 2B DD	Level 2A PD	Level 2B DD	Level 2A PD	Level 2B DD	Level 2A - PD - Average method	Level 2B - DD - LCA detailed quantitative report
LCA Stage		A1-A3		A4-A5		B		C		D		Total	
Environmental Indicators	Functional Unit												
GWPF	kg CO ₂ eq.	2,40E+06 61,65 %	1,49E+06 38,35 %	9,16E+04 34,65 %	1,73E+05 65,35 %	2,33E+02 0,33 %	7,02E+04 99,67 %	1,33E+05 43,86 %	1,70E+05 56,14 %	-1,84E+06 47,31 %	-2,04E+06 52,69 %	7,88E+05 123,99 %	-1,52E+05 -23,99 %
GWPb	kg CO ₂ eq.	-2,97E+06 49,59 %	-3,02E+06 50,41 %	4,62E+04 50,97 %	4,44E+04 49,03 %	3,84E+00 3,96 %	9,31E+01 96,04 %	2,63E+06 46,98 %	2,97E+06 53,02 %	-6,99E+05 83,01 %	-1,43E+05 16,99 %	-9,87E+05 91,07 %	-9,69E+04 8,93 %
GWPI	kg CO ₂ eq.	4,59E+04 111,08 %	-4,58E+03 -11,08 %	1,04E+02 17,76 %	4,80E+02 82,24 %	9,02E-01 2,67 %	3,29E+01 97,33 %	2,61E+02 1,38 %	1,87E+04 98,62 %	-6,57E+02 6,38 %	-9,64E+03 93,62 %	4,56E+04 90,26 %	4,92E+03 9,74 %
GWPT	kg CO ₂ eq.	1,28E+06 68,97 %	5,75E+05 31,03 %	1,28E+05 36,66 %	2,21E+05 63,34 %	2,38E+02 0,34 %	7,03E+04 99,66 %	1,27E+06 55,10 %	1,03E+06 44,90 %	-1,98E+06 48,19 %	-2,13E+06 51,81 %	-5,64E+05 74,00 %	-1,98E+05 26,00 %
ADPF	MJ	3,78E+07 61,69 %	2,35E+07 38,31 %	1,22E+06 36,33 %	2,13E+06 63,67 %	4,68E+03 0,31 %	1,49E+06 99,69 %	1,57E+06 47,42 %	1,74E+06 52,58 %	-2,69E+07 47,59 %	-2,97E+07 52,41 %	1,36E+07 107,49 %	-9,51E+05 -7,49 %
ADPm/ADPE	kg Sb eq	7,17E+00 42,42 %	9,73E+00 57,58 %	2,97E-01 10,15 %	2,63E+00 89,85 %	2,00E-03 0,25 %	7,93E-01 99,75 %	1,36E-01 4,16 %	3,14E+00 95,84 %	-8,09E+05 100,00 %	2,65E+00 0,00 %	-8,09E+05 100,00 %	1,89E+01 0,00 %
AP	mol H+ eq.	1,24E+04 52,63 %	1,12E+04 47,37 %	3,34E+02 20,05 %	1,33E+03 79,95 %	1,83E+00 0,37 %	4,95E+02 99,63 %	7,25E+02 44,35 %	9,10E+02 55,65 %	-8,34E+03 54,14 %	-7,07E+03 45,86 %	5,12E+03 42,99 %	6,79E+03 57,01 %
EpF	kg P eq.	2,30E+02 38,68 %	3,64E+02 61,32 %	2,41E+00 6,99 %	3,20E+01 93,01 %	5,20E-02 0,25 %	2,04E+01 99,75 %	1,37E+01 35,48 %	2,49E+01 64,52 %	-7,02E+01 19,36 %	-2,92E+02 80,64 %	1,76E+02 54,08 %	1,49E+02 45,92 %
EPm	kg N eq.	3,13E+03 54,68 %	2,59E+03 45,32 %	1,04E+02 23,07 %	3,47E+02 76,93 %	3,50E-01 0,39 %	8,83E+01 99,61 %	3,26E+02 51,46 %	3,07E+02 48,54 %	-1,13E+03 48,92 %	-1,18E+03 51,08 %	2,43E+03 53,12 %	2,14E+03 46,88 %
EPT	mol N eq.	2,77E+04 51,23 %	2,63E+04 48,77 %	1,11E+03 22,69 %	3,77E+03 77,31 %	3,08E+00 0,46 %	6,67E+02 99,54 %	2,99E+03 46,47 %	3,44E+03 53,53 %	-1,48E+04 56,59 %	-1,14E+04 43,41 %	1,70E+04 42,70 %	2,28E+04 57,30 %
ODP	kg CFC-11 eq.	1,04E-01 41,60 %	1,46E-01 58,40 %	2,65E+01 99,92 %	2,20E-02 0,08 %	1,71E-05 0,14 %	1,20E-02 99,86 %	8,00E-03 36,36 %	1,40E-02 63,64 %	-1,33E-01 30,23 %	-3,07E-01 69,77 %	2,65E+01 100,43 %	-1,13E-01 -0,43 %
POCP	kg C ₂ H ₄	7,33E+03 46,83 %	8,32E+03 53,17 %	2,85E+02 21,54 %	1,04E+03 78,46 %	9,62E-01 0,37 %	2,59E+02 99,63 %	7,98E+02 48,99 %	8,32E+02 51,01 %	-3,58E+03 45,31 %	-4,32E+03 54,69 %	7,93E+03 56,54 %	6,09E+03 43,46 %
WDP	m ³ world eq.	9,38E+05 50,73 %	9,11E+05 49,27 %	1,01E+04 32,52 %	2,10E+04 67,48 %	1,25E+03 0,23 %	5,46E+05 99,77 %	9,17E+04 50,40 %	9,02E+04 49,60 %	-3,37E+05 55,56 %	-2,70E+05 44,44 %	7,04E+05 35,22 %	1,30E+06 64,78 %
PERT	MJ	7,55E+07 52,51 %	6,83E+07 47,49 %	4,20E+04 16,25 %	2,16E+05 83,75 %	2,87E+02 0,46 %	6,19E+04 99,54 %	-1,82E+06 20,46 %	-7,07E+06 79,54 %	-9,41E+06 75,33 %	-3,08E+06 24,67 %	6,43E+07 52,41 %	5,84E+07 47,59 %
PENRT	MJ	3,87E+07 61,32 %	2,44E+07 38,68 %	1,24E+06 35,38 %	2,27E+06 64,62 %	5,39E+03 0,29 %	1,83E+06 99,71 %	1,58E+06 47,51 %	1,75E+06 52,49 %	-2,90E+07 47,82 %	-3,17E+07 52,18 %	1,25E+07 113,98 %	-1,54E+06 -13,98 %

The proposed average EPD for early design phases involves converting specific EPDs for construction. This approach addresses the challenges of anonymous materials for public procurement and the lack of specific data to perform LCA. It also contributes to the implementation of EPBD [24] within the European framework. From a policymakers perspective, the plugin development aligns with the EU's sustainability targets and relevant directives, such as Level(s) and the EPBD. Consequently, it supports AEC professionals in achieving regulatory compliance while improving environmental performance.

The integration of RE2020 and of the EPBD into national frameworks marks an important step toward harmonizing energy performance and embodied carbon assessment across Europe. However, policymakers will only unlock the full potential of these measures if they take decisive action to accelerate the transformation. A key lever lies in public procurement, where mandating the use of average EPDs can establish a transparent baseline and incentivize low-carbon design choices. By mandating the use of average EPD governments can set a clear baseline, driving transparency, and reward AEC stakeholders who outperform LCA benchmarks throughout the design phases. We therefore reinforce the need for a coordinated policy shift in which average EPDs are formally adopted in procurement procedures, initially in public projects and progressively in all construction sectors. Such an approach would not only encourage innovation and decarbonization in the construction industry but also demonstrate public leadership in aligning the built environment with Europe's climate goals.

BIM adoption positively impacts collaboration, accuracy, and decision-making at every phase. The successful implementation of the proposed LOIN framework adds another layer of efficiency to the BIM process, contributing to a more sustainable and streamlined construction industry.

When BIM models comply with the detail, information, and classification criteria established in previous sections, users no longer need to prepare the models before running a BIM-LCA tool to obtain LCA results. The results will be as precise as the designed model, and the information it contains.

The findings from the previous sections are implemented in a BIM tool in a semiautomatic way. Specifically, by allowing the designer to choose 3–10 EPDs of the same material. The BIM tool enables the automatic calculation of the average for a generic material to be used in an intermediate design phase. The first step automatically converts all the EPDs to the same functional units. Concerning the remaining restrictions of harmonization presented in Table 3, such as the standard to be used, the EPD choice should be restricted such that all EPDs refer to the same standard (e.g., ISO 14025:2006 [6] and EN 15804:2012 + A2:2019/AC:2021 [7]). Furthermore, restrictions are recommended for maintaining the same PCR (e.g., CEN standard EN 15804:2012 + A2:2019/AC:2021 [7]) and only valid EPDs should be displayed. One of the limitations of the current study is the number of EPDs available for different materials, which restricts the data collection of EPDs for average calculations. Although some materials are highly studied in terms of EPDs, most of the materials are not represented.

Despite these limitations, the proposed approach demonstrates strong potential for supporting early-phase decision-making, particularly in contexts where data availability is limited.

This scarcity is the main reason why the average EPD was limited to 3, 5 or 10 EPDs to obtain consistency samples, the same number of samples, for each of the materials proposed in a building construction. In conclusion, given the limited number of EPDs available, we recommend increasing the number of EPDs to evaluate the average values using a larger database of materials with available EPDs.

The case study reflects the novelty of the manuscript in terms of the different phases and different decisions made during the

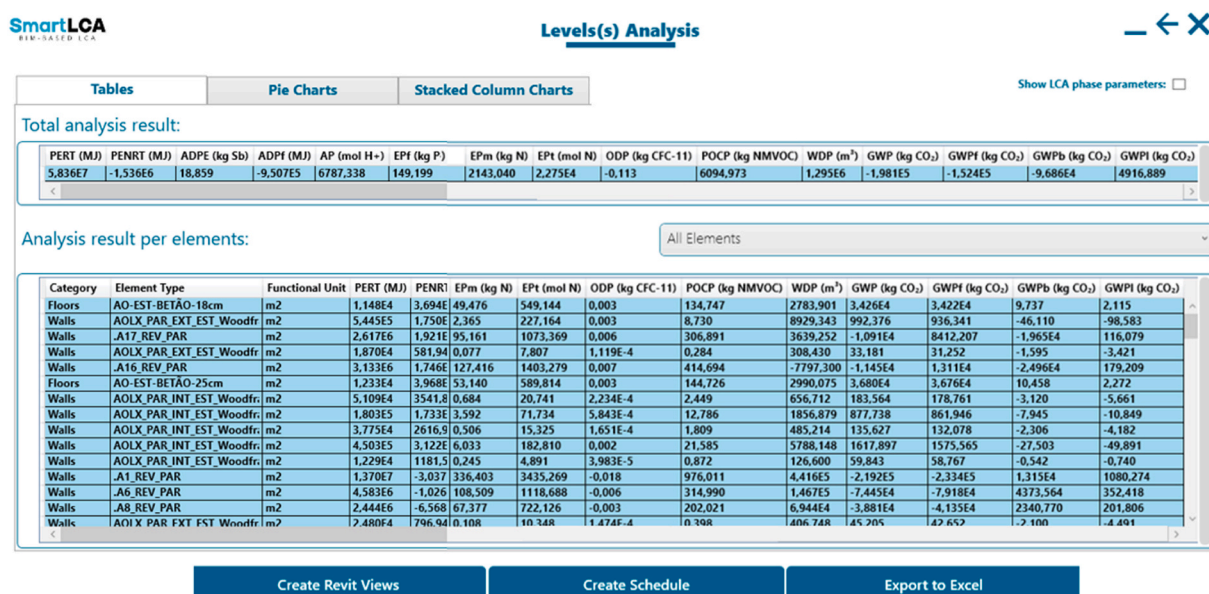


Fig. 25. - Detail design with Level 2B total project LCA results (schedule above) to address the issue of assigning data to each BIM object (schedule below).

process, specifically by dividing Level 2 into two distinct analyses.

- **Level 2A:** This level consists of design development (concept design and spatial coordination) and serves as an intermediate level. No restrictions should be applied regarding the number of average EPD formulations used in a project. This phase provides the first LCA quantitative results to support designers in making decisions about material choices and anticipating impact outcomes. While designers can still modify material choices, no final specification is required at this phase. Testing different material options enables them to access the sensitivity of environmental impacts before making final decision, thereby supporting effective decision-making. In conclusion, this approach enables disruptive material changes as LCA becomes integrated into design development.
- **Level 2B:** This level encompasses technical design. In this phase, designers must replace average or generic materials with final decision on the material option and the corresponding specific EPD. Additionally, at this phase, the BIM model contains a higher level of detail, enabling more precise quantified results of material impacts.

In addition to the automatic calculation of results [34], the integration of a BIM tool is designed to be user friendly and accessible not only to be used by LCA specialists but also to support professionals who seek to make better environmental decisions and reduce carbon impacts as the design progress. The proposal consists of providing average graphics, such as Figs. 20, Figure 21, Fig. 22, to help users to visually verify the variations between average samples. Furthermore, this graphical perspective enables a transition from Level 2A to 2B according to Table 5 per material option, or Table 6 for overall case study comparisons between different material design options and graphical representations. The opportunity to test the proposed division phases, including average aligning of the LOIN with LCA, where to test different materials in a real-life case study, influences the design team's decision-making, with fewer environmental impacts. This approach, both quantitative and graphical, serves as a positive proof of concept.

These steps enable a more informed decision regarding the final LCA results at Level 2B once the BIM model reaches a higher level of detail for construction, allowing a precise BoQ for LCA (Table 7, Fig. 25, and Fig. 26).

The implementation of the findings from Table 3, Tables 4 and 5 into a BIM-LCA tool connected to an online database provides an additional contribution, enabling the user to search online and select three, five, or ten options. The BIM tool automatically calculates the average value and applies the material to the BIM model as an average EPD for the preliminary design phase. It then converts this value to a specific EPD at the construction phase, expediting the LCA process and allowing additional time for intermediate analysis to identify optimized solutions.

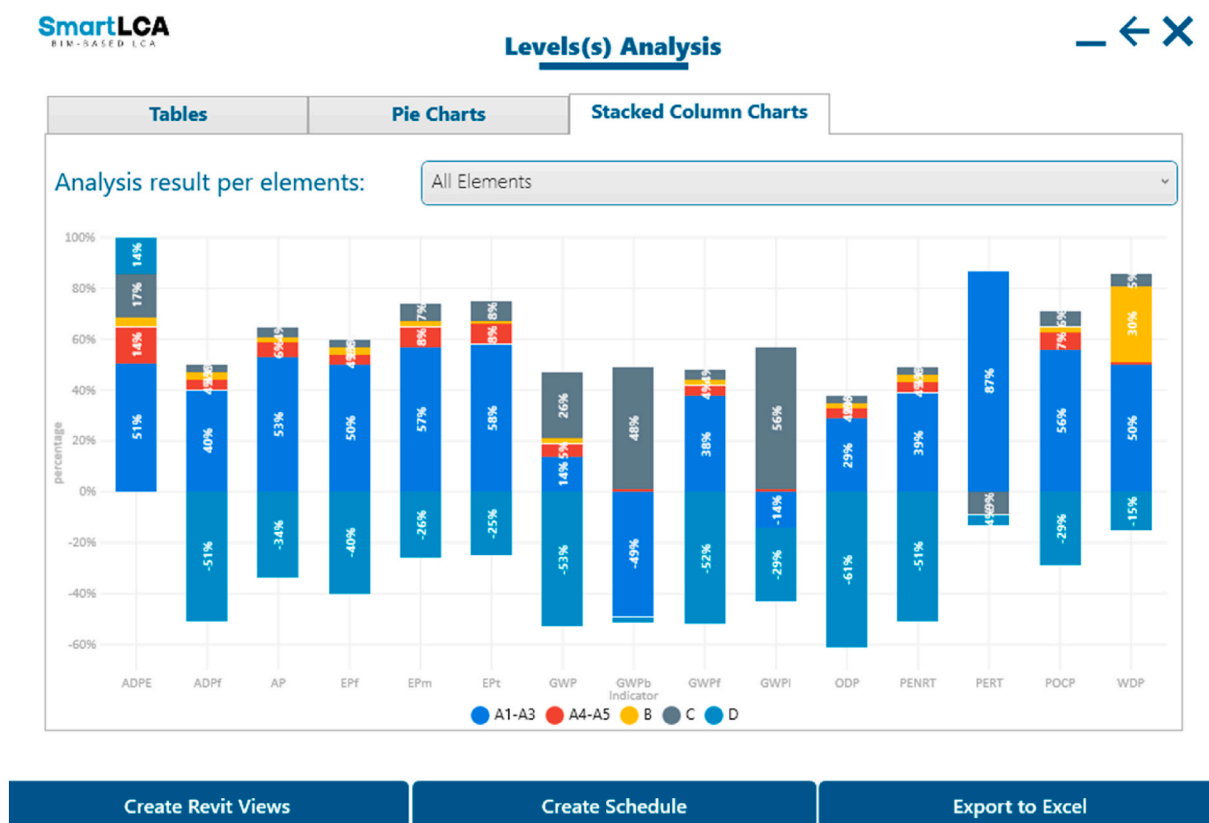


Fig. 26. Detail design with Level 2B total project LCA results stacked column charts, per LCA stage and environmental indicator for a graphical visualization of LCA results.

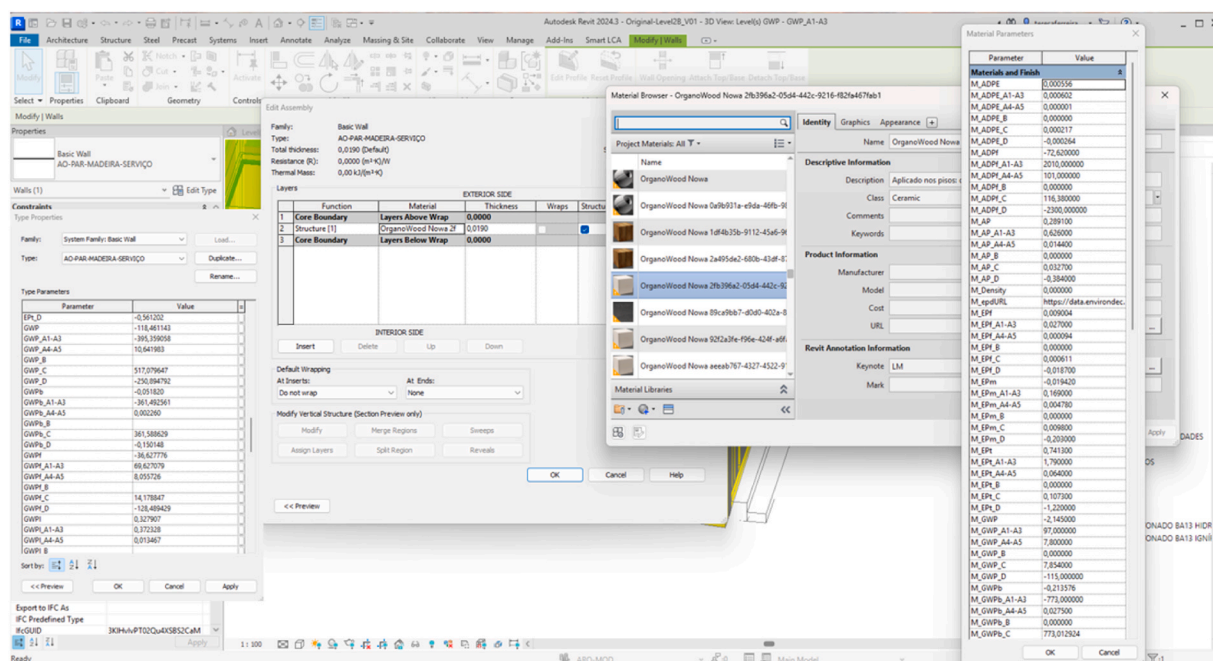


Fig. 27. Level 2B: EPD addressed with environmental impacts per indicator in the wall BIM object and each material constituent to address the issue of specific EPD data assignment to BIM objects and materials.

However, additional systemic barriers persist. In low-digital-maturity regions, inadequate digital infrastructure, limited computational capacity, and fragmented data standards continue to hinder BIM-LCA integration. In public procurement workflows, the absence of harmonized rules for using generic or average EPDs restricts the implementation of intermediate LCA assessments. Addressing these obstacles will be essential to ensuring equitable adoption of BIM-LCA across Europe.

From a training perspective, coherent upskilling strategies are required. Designers and engineers must acquire BIM modelling and LCA proficiency. Contractors require practical training in data interpretation and material documentation. Procurement officers must understand EPD structures and selection criteria, and policymakers need foundational training in BIM-LCA interoperability to interpret results and design effective regulatory frameworks.

In conclusion, by addressing the issue of public procurement and data management, we recommend a call to action for policy makers, through the formal adoption of average EPDs.

Overall, this study reinforces the need for integrated digital and environmental strategies across all design phases. Future research should explore broader datasets, additional case studies, and the implications of scaling the framework to large infrastructure projects. Such efforts would further validate the robustness and adaptability of the proposed approach and strengthen its contribution to sustainable construction practices.

CRediT authorship contribution statement

Maria Teresa H.A. Ferreira: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **António Aguiar Costa:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis. **José Dinis Silvestre:** Writing – review & editing, Validation, Supervision, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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9. Attachment

Table A. 1 is a compiled table containing the data from the selected EPD (Table 3) necessary to generate Figs. 14, Figure 15, Fig. 16 and the average results presented in Table 4.

Table A. 1

EPD average values for wood materials in the 3, 5 and 10 datasets.

Indicator	Unit	Material	A1-A3	C2	C3	C4	D
GWP-fossil	kg CO ₂ eq.	Wood 1	1.11E + 02	7.77E-01	2.78E + 01	0.00E + 00	-2.76E + 02
		Wood 2	1.40E + 02	1.48E + 00	3.64E + 00	0.00E + 00	-4.10E + 02
		Wood 3	1.14E + 02	1.42E + 00	3.49E + 00	0.00E + 00	-4.01E + 02
		Wood 4	5.26E + 01	2.04E + 00	2.02E + 01	0.00E + 00	-2,67E + 2
		Wood 5	1.33E + 02	1.08E + 01	1.49E-04	0.00E + 00	-6.04E + 00
		Wood 6	1.93E + 02	8.60E + 01	4.80E + 00	1.60E-01	-1.70E + 02
		Wood 7	2.07E + 02	1.90E + 01	1.15E + 01	0.00E + 00	2.56E + 02
		Wood 8	6.26E + 01	8.21E + 00	1.21E + 01	2.74E-01	-3.39E + 01
		Wood 9	8.53E + 01	3.97E + 00	1.36E + 01	0.00E + 00	-2.65E + 02
		Wood 10	9.46E + 01	8.21E + 00	1.20E + 01	2.74E-01	-3.66E + 01
		Average 3EPD	1.22E + 02	1.23E + 00	1.16E + 01	0.00E + 00	-3.62E + 02
		Average 5EPD	1.10E + 02	3.30E + 00	1.10E + 01	0.00E + 00	-2.19E + 02
		Average 10EPD	1.19E + 02	1.42E + 01	1.09E + 01	7.08E-02	-1.60E + 02
GWP-biogenic	kg CO ₂ eq.	Wood 1	-8.57E + 02	4.16E-04	9.85E-03	8.58E + 02	0.00E + 00
		Wood 2	-8.06E + 02	6.47E-02	8.09E + 02	0.00E + 00	-2.66E + 01
		Wood 3	-7.78E + 02	0.00E + 00	7.83E + 02	0.00E + 00	-2.29E + 00
		Wood 4	-7.62E + 02	8.12E-04	7.62E + 02	0.00E + 00	-7.51E-01
		Wood 5	-8.04E + 02	6.32E-03	8.04E + 02	0.00E + 00	-6.57E + 02
		Wood 6	-1.10E + 03	2.30E-02	6.30E + 02	5.90E + 00	-1.80E + 01
		Wood 7	7.13E + 02	0.00E + 00	7.13E + 02	0.00E + 00	0.00E + 00
		Wood 8	-7.59E + 02	3.52E-03	7.22E + 02	4.00E + 01	0.00E + 00
		Wood 9	-7.62E + 02	0.00E + 00	7.62E + 02	0.00E + 00	0.00E + 00
		Wood 10	-7.59E + 02	3.52E-03	7.22E + 02	4.00E + 01	0.00E + 00
		Average 3EPD	-8.14E + 02	2.17E-02	5.31E + 02	2.86E + 02	-9.62E + 00
		Average 5EPD	-8.01E + 02	1.44E-02	6.32E + 02	1.72E + 02	-1.37E + 02
		Average 10EPD	-7.39E + 02	1.02E-02	6.71E + 02	9.44E + 01	-7.05E + 01
GWP-luluc	kg CO ₂ eq.	Wood 1	2.96E + 00	2.74E-02	7.89E-02	0.00E + 00	-2.67E-02
		Wood 2	2.51E-01	9.97E-03	7.69E-04	0.00E + 00	-4.89E-02
		Wood 3	2.97E-01	9.56E-03	7.38E-04	0.00E + 00	-4.90E-02
		Wood 4	8.78E-01	7.67E-04	2.27E-03	0.00E + 00	-2.77E-01
		Wood 5	8.96E-01	3.40E-03	2.16E-08	0.00E + 00	-1.01E-03
		Wood 6	1.37E + 00	1.60E-03	5.80E-04	3.90E-06	-3.30E-01
		Wood 7	6.86E01	1.57E01	7.38E03	0.00E + 00	1.75E01
		Wood 8	1.56E + 00	2.91E-03	1.94E-03	1.17E-04	-3.44E-01
		Wood 9	2.09E + 00	1.23E-03	1.75E-03	0.00E + 00	-2.50E-01
		Wood 10	1.63E + 00	2.91E-03	1.94E-03	1.17E-04	-3.47E-01
		Average 3EPD	1.17E + 00	1.56E-02	2.68E-02	0.00E + 00	-4.15E-02
		Average 5EPD	1.06E + 00	1.02E-02	1.65E-02	0.00E + 00	-8.05E-02
		Average 10EPD	1.19E + 00	5.98E-03	8.89E-03	2.38E-05	-1.67E-01
GWP-total	kg CO ₂ eq.	Wood 1	-7.43E + 02	8.05E-01	2.78E + 01	8.58E + 02	-2.76E + 02
		Wood 2	-6.65E + 02	1.56E + 00	8.13E + 02	0.00E + 00	-4.36E + 02
		Wood 3	-6.64E + 02	1.43E + 00	7.87E + 02	0.00E + 00	-4.04E + 02
		Wood 4	-7.08E + 02	2.05E + 00	7.82E + 02	0.00E + 00	-2.68E + 02
		Wood 5	-6.70E + 02	1.08E + 01	1.49E-04	0.00E + 00	-6.63E + 02
		Wood 6	-9.04E + 02	8.60E + 01	6.40E + 02	6.50E + 00	-1.90E + 02
		Wood 7	5.05E + 02	1.91E + 01	7.25E + 02	0.00E + 00	-2.56E + 02
		Wood 8	-6.95E + 02	8.22E + 00	7.34E + 02	4.03E + 01	-3.43E + 01
		Wood 9	-6.75E + 02	3.97E + 00	7.76E + 02	0.00E + 00	-2.65E + 02
		Wood 10	-6.62E + 02	8.22E + 00	7.34E + 02	4.03E + 01	-3.70E + 01
		Average 3EPD	-6.91E + 02	1.27E + 00	5.42E + 02	2.86E + 02	-3.72E + 02
		Average 5EPD	-5.56E + 02	1.17E + 00	4.82E + 02	1.72E + 02	-2.77E + 02
		Average 10EPD	-6.39E + 02	1.42E + 01	6.02E + 02	9.45E + 01	-2.83E + 02
ODP	kg CFC 11 eq.	Wood 1	5.08E-06	2.80E-08	3.88E-07	0.00E + 00	-7.35E-06
		Wood 2	2.69E-09	1.45E-13	5.32E-11	0.00E + 00	-3.17E-09
		Wood 3	8.42E-10	1.39E-13	5.11E-11	0.00E + 00	-3.18E-09

(continued on next page)

Table A. 1 (continued)

Indicator	Unit	Material	A1-A3	C2	C3	C4	D
AP	mol H + eq.	Wood 4	9.15E-06	5.10E-07	1.75E-06	0.00E + 00	-2.86E-05
		Wood 5	5.75E-02	1.72E-02	3.23E-02	3.64E-07	0.00E + 00
		Wood 6	3.17E-05	1.90E-05	2.90E-07	3.50E-08	-8.40E-06
		Wood 7	2.05E07	3.79E15	1.02E13	0.00E + 00	2.88E12
		Wood 8	9.37E-06	1.89E-06	5.11E-07	7.72E-08	-8.04E-06
		Wood 9	1.57E-05	8.94E-07	5.83E-07	0.00E + 00	-3.00E-05
		Wood 10	1.07E-05	1.89E-06	5.10E-07	7.72E-08	-8.25E-06
		Average 3EPD	1.69E-06	9.33E-09	1.29E-07	0.00E + 00	-2.45E-06
		Average 5EPD	1.15E-02	3.44E-03	6.46E-03	7.28E-08	-7.19E-06
		Average 10EPD	5.76E-03	1.72E-03	3.23E-03	5.53E-08	-9.06E-06
		Wood 1	2.21E + 01	3.78E-03	1.41E-01	0.00E + 00	-2.40E-01
		Wood 2	4.98E-01	4.95E-03	7.99E-03	0.00E + 00	3.39E-01
		Wood 3	6.74E-01	4.74E-03	7.66E-03	0.00E + 00	3.58E-01
		Wood 4	3.11E-01	6.51E-03	2.04E-01	0.00E + 00	-7.43E-01
		Wood 5	1.21E-03	1.47E-04	7.07E-04	8.16E-09	0.00E + 00
		Wood 6	1.20E + 00	5.40E-01	6.30E-02	1.70E-03	-9.70E-01
		Wood 7	6.38E01	1.02E01	1.11E01	0.00E + 00	3.31E01
		Wood 8	4.88E-01	4.68E-02	1.21E-01	2.15E-03	-4.75E-01
		Wood 9	6.75E-01	1.63E-02	1.52E-01	0.00E + 00	-6.44E-01
		Wood 10	5.90E-01	4.68E-02	1.21E-01	2.15E-03	-5.21E-01
EP-freshwater	kg P eq.	Average 3EPD	7.76E + 00	4.49E-03	5.22E-02	0.00E + 00	1.52E-01
		Average 5EPD	4.72E + 00	4.03E-03	7.23E-02	1.63E-09	-5.72E-02
		Average 10EPD	2.65E + 00	6.70E-02	8.18E-02	6.00E-04	-2.90E-01
		Wood 1	6.52E-02	7.55E-05	5.04E-03	0.00E + 00	-4.95E-03
		Wood 2	4.08E-04	5.29E-06	1.06E-05	0.00E + 00	-6.39E-04
		Wood 3	2.24E-03	5.07E-06	1.02E-05	0.00E + 00	-6.40E-04
		Wood 4	6.35E-03	1.46E-05	1.01E-04	0.00E + 00	-1.25E-02
		Wood 5	2.77E-02	1.08E-02	1.19E-07	0.00E + 00	-3.78E-02
		Wood 6	5.11E-02	3.30E-04	2.40E-03	2.80E-04	-1.70E-01
		Wood 7	1.2E03	5.7E05	1.4E05	0.00E + 00	3.3E04
		Wood 8	1.66E-02	6.76E-05	1.15E-04	5.20E-06	-3.27E-03
		Wood 9	2.72E-02	3.07E-04	2.86E-03	0.00E + 00	-1.05E-01
		Wood 10	2.17E-02	6.76E-05	1.15E-04	5.20E-06	-3.52E-03
		Average 3EPD	2.26E-02	2.86E-05	1.69E-03	0.00E + 00	-2.08E-03
		Average 5EPD	2.04E-02	2.18E-03	1.03E-03	0.00E + 00	-1.13E-02
		Average 10EPD	2.18E-02	1.17E-03	1.07E-03	2.90E-05	-3.38E-02
EP-marine	kg N eq.	Wood 1	3.48E-01	1.58E-03	4.83E-02	0.00E + 00	-8.78E-02
		Wood 2	2.45E-01	2.26E-03	1.79E-03	0.00E + 00	7.35E-02
		Wood 3	3.17E-01	2.17E-03	1.72E-03	0.00E + 00	8.45E-02
		Wood 4	9.19E-02	1.43E-03	9.41E-02	0.00E + 00	-1.17E-01
		Wood 5	3.02E-01	1.18E-01	1.29E-06	0.00E + 00	-3.62E-01
		Wood 6	3.43E-01	2.20E-01	3.50E-02	1.30E-02	-1.90E-01
		Wood 7	2.66E01	4.92E02	3.63E02	0.00E + 00	9.45E02
		Wood 8	1.67E-01	1.67E-02	5.54E-02	1.42E-03	-1.56E-01
		Wood 9	2.49E-01	4.68E-03	7.79E-02	0.00E + 00	-1.27E-01
		Wood 10	1.86E-01	1.67E-02	5.54E-02	1.42E-03	-1.70E-01
		Average 3EPD	3.03E-01	2.00E-03	1.73E-02	0.00E + 00	2.34E-02
		Average 5EPD	2.61E-01	2.51E-02	2.92E-02	0.00E + 00	-8.18E-02
		Average 10EPD	2.25E-01	3.84E-02	3.70E-02	1.58E-03	-1.05E-01
EP-terrestrial	mol N eq.	Wood 1	2.21E + 00	1.45E-02	5.17E-01	0.00E + 00	-9.53E-01
		Wood 2	2.47E + 00	2.53E-02	1.88E-02	0.00E + 00	8.71E-01
		Wood 3	2.95E + 00	2.43E-02	1.80E-02	0.00E + 00	9.91E-01
		Wood 4	1.06E + 00	1.59E-02	1.07E + 00	0.00E + 00	-1.32E + 00
		Wood 5	1.13E-01	5.11E-02	6.10E-07	0.00E + 00	-9.06E-02
		Wood 6	3.49E + 00	2.40E + 00	3.40E-01	8.30E-03	-1.70E + 00
		Wood 7	2.87E + 00	5.45E01	5.27E01	0.00E + 00	1.01E + 00
		Wood 8	1.73E + 00	1.84E-01	6.35E-01	7.96E-03	-2.17E + 00
		Wood 9	2.70E + 00	5.14E-02	8.17E-01	0.00E + 00	-1.17E + 00
		Wood 10	2.00E + 00	1.84E-01	6.35E-01	7.96E-03	-2.39E + 00
		Average 3EPD	2.54E + 00	2.14E-02	1.85E-01	0.00E + 00	3.03E-01
		Average 5EPD	1.76E + 00	2.62E-02	3.25E-01	0.00E + 00	-1.00E-01
		Average 10EPD	2.16E + 00	2.95E-01	4.05E-01	2.42E-03	-7.93E-01
POCP	kg NMVOC eq.	Wood 1	1.18E + 00	5.44E-03	1.69E-01	0.00E + 00	-6.14E-01
		Wood 2	8.89E-01	4.44E-03	4.84E-03	0.00E + 00	3.12E-01
		Wood 3	1.05E + 00	4.26E-03	4.65E-03	0.00E + 00	3.51E-01
		Wood 4	4.65E-01	6.27E-03	2.82E-01	0.00E + 00	-3.90E-01
		Wood 5	3.58E-07	7.71E-08	2.16E-07	2.85E-12	0.00E + 00
		Wood 6	1.25E + 00	8.60E-01	8.00E-02	3.90E-03	-5.00E-01
		Wood 7	7.67E01	9.56E02	9.87E02	0.00E + 00	2.65E01
		Wood 8	5.85E-01	5.27E-02	1.66E-01	2.85E-03	-4.91E-01

(continued on next page)

Table A. 1 (continued)

Indicator	Unit	Material	A1-A3	C2	C3	C4	D
ADP minerals & metals	kg Sb eq.	Wood 9	1.23E+00	1.57E-02	2.12E-01	0.00E+00	-3.53E-01
		Wood 10	6.43E-01	5.27E-02	1.66E-01	2.85E-03	-5.29E-01
		Average 3EPD	1.04E+00	4.71E-03	5.95E-02	0.00E+00	1.62E-02
		Average 5EPD	7.17E-01	4.08E-03	9.21E-02	5.70E-13	-6.83E-02
		Average 10EPD	7.29E-01	1.00E-01	1.08E-01	9.60E-04	-2.21E-01
		Wood 1	6.74E-04	2.52E-06	7.44E-05	0.00E+00	-1.33E-04
		Wood 2	3.00E-05	1.49E-07	9.91E-07	0.00E+00	-6.80E-05
		Wood 3	4.63E-05	1.43E-07	9.50E-07	0.00E+00	-6.77E-05
		Wood 4	2.21E-04	4.89E-06	2.00E-05	0.00E+00	-1.40E-04
		Wood 5	7.47E-05	3.44E-05	2.35E-10	0.00E+00	-1.02E-05
		Wood 6	2.12E-04	3.60E-06	2.50E-06	8.10E-09	-1.10E-05
		Wood 7	7.68E05	1.7E06	1.55E06	0.00E+00	4.21E05
		Wood 8	1.71E-03	2.12E-04	2.38E-05	2.64E-06	-4.59E-04
		Wood 9	5.23E-04	1.17E-05	1.75E-05	0.00E+00	-2.63E-04
		Wood 10	2.00E-03	2.12E-04	2.38E-05	2.64E-06	-4.74E-04
		Average 3EPD	2.50E-04	9.37E-07	2.54E-05	0.00E+00	-8.96E-05
		Average 5EPD	2.09E-04	8.42E-06	1.93E-05	0.00E+00	-8.38E-05
		Average 10EPD	5.49E-04	4.81E-05	1.64E-05	5.29E-07	-1.63E-04
ADP-fossil	MJ	Wood 1	1.70E+03	1.19E+01	3.87E+02	0.00E+00	-4.16E+03
		Wood 2	2.20E+03	1.94E+01	6.60E+01	0.00E+00	-7.08E+03
		Wood 3	1.88E+03	1.86E+01	6.33E+01	0.00E+00	-6.95E+03
		Wood 4	8.16E+02	3.33E+01	1.21E+02	0.00E+00	-5.07E+03
		Wood 5	8.87E+01	1.20E+01	1.43E-04	0.00E+00	-1.06E+01
		Wood 6	3.30E+03	1.20E+03	3.70E+01	2.20E+00	-3.60E+03
		Wood 7	2.89E+03	2.55E+02	1.69E+02	0.00E+00	4.43E+03
		Wood 8	9.43E+02	1.26E+02	4.38E+01	5.89E+00	-4.59E+02
		Wood 9	1.41E+03	5.96E+01	4.68E+01	0.00E+00	-4.93E+03
		Wood 10	1.39E+03	1.26E+02	4.37E+01	5.89E+00	-5.00E+02
		Average 3EPD	1.93E+03	1.67E+01	1.72E+02	0.00E+00	-6.06E+03
		Average 5EPD	1.34E+03	1.91E+01	1.27E+02	0.00E+00	-4.65E+03
		Average 10EPD	1.66E+03	1.86E+02	9.78E+01	1.40E+00	-3.28E+03
WDP	m ³	Wood 1	2.86E+01	1.49E-01	2.69E+00	0.00E+00	-1.02E+01
		Wood 2	1.33E+01	1.66E-02	8.29E-01	0.00E+00	-2.33E+01
		Wood 3	1.59E+01	1.59E-02	7.95E-01	0.00E+00	-2.22E+01
		Wood 4	2.09E+01	1.11E-01	1.21E+00	0.00E+00	-2.79E+01
		Wood 5	1.23E+00	1.43E-01	5.73E-01	5.10E-06	0.00E+00
		Wood 6	4.62E+01	1.20E-01	-5.50E+00	5.50E-04	-4.00E+01
		Wood 7	1.46E+01	1.78E01	8.05E+01	0.00E+00	1.91E+01
		Wood 8	3.22E+01	3.87E-01	1.39E+00	2.51E-01	-4.92E+00
		Wood 9	3.28E+03	3.84E-01	1.12E+00	0.00E+00	-2.40E+01
		Wood 10	3.40E+01	3.87E-01	1.39E+00	2.51E-01	-5.09E+00
		Average 3EPD	1.93E+01	6.05E-02	1.44E+00	0.00E+00	-1.86E+01
		Average 5EPD	1.60E+01	8.71E-02	1.22E+00	1.02E-06	-1.67E+01
		Average 10EPD	3.49E+02	1.71E-01	8.50E+00	5.03E-02	-1.58E+01

Data availability

Data will be made available on request.

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