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Barriers to whole-life carbon implementation in construction: A systematic literature review with Baltic regional contextualisation

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A R T I C L E I N F O

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A B S T R A C T

The increasing significance of embodied emissions has shifted the focus of the construction sector from operational energy towards Whole-Life Carbon (WLC) assessment, which evaluates greenhouse gas emissions across the entire building life cycle. This transition is reinforced by recent European policy developments, including the revised Energy Performance of Buildings Directive (EPBD), the Level(s) framework, and the EN 15978 standard. Despite methodological advancements and the growing integration of Building Information Modelling and Life Cycle Assessment (BIM-LCA), the practical implementation of WLC assessment remains inconsistent, particularly in smaller construction markets.

This study investigates barriers to WLC implementation in the Baltic construction sector through a qualitative systematic literature review following the PRISMA 2020 framework. The review synthesises evidence from 58 peer-reviewed studies and 16 policy and institutional documents addressing WLC assessment, BIM-LCA integration, and regulatory frameworks.

The findings identify three interrelated groups of barriers. Digital barriers include limited interoperability between BIM and LCA tools, fragmented data structures, and low levels of workflow automation. Policy barriers arise from inconsistencies in the interpretation and operationalisation of EPBD, Level(s), and EN 15978 requirements across national contexts, as well as limited availability of empirical data for benchmarking. Socio-cultural barriers, including skills gaps, institutional inertia, and cost-driven decision-making, further constrain the integration of WLC approaches into routine construction practice.

The results indicate that WLC implementation is constrained not by isolated factors but by misalignment between digital capabilities, regulatory frameworks, and sectoral competencies. The study contributes by providing an integrated socio-technical perspective on WLC barriers in smaller construction markets and highlights the need for coordinated development of data infrastructures, methodological standards, and professional capacities to enable effective adoption.

1. Introduction

The decarbonization of the construction sector has become a central element of global climate mitigation strategies, as buildings generate substantial greenhouse gas emissions across their entire life cycle. While earlier policies and research primarily focused on reducing operational energy consumption, recent studies show that embodied energy and carbon associated with material production, construction processes, maintenance, and end-of-life stages account for a significant share of total building-related impacts [1–3]. As energy efficiency requirements continue to reduce operational energy demand, the relative importance of assessing emissions across the full life cycle of buildings has increased.

WLC assessment has become increasingly important in the shift towards more comprehensive approaches to building decarbonization, as it brings operational and embodied emissions into a single evaluation framework. This direction is reinforced by current European policy developments. The revised EPBD together with the Level(s) framework promotes life-cycle-based assessment of building performance and encourages the integration of carbon-related criteria into national regulatory and reporting systems. Methodological standards such as EN

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15978 further support this process by providing a common structure for assessing environmental impacts across the main life-cycle stages of buildings. Recent research also reflects growing interest in design strategies and building solutions aimed at reducing emissions across the full building life cycle [4]. Even so, the practical uptake of WLC assessment remains uneven across national contexts.

Digitalization is increasingly recognized as an important condition for the practical application of life-cycle carbon assessment in the construction sector. In this context, the integration of BIM and LCA has attracted growing attention because it allows quantity information, material data, and environmental indicators to be connected within the design process. Such integration can support earlier and more informed decisions on material selection, design alternatives, and environmental performance. Previous studies have shown that BIM-LCA workflows can improve the evaluation of sustainability options already at the design stage, including the comparison of alternative construction solutions and their carbon implications [5]. At the same time, the literature consistently shows that this potential is not yet fully realized in practice. Systematic reviews identify recurring limitations related to interoperability between BIM and LCA tools, inconsistencies in data structures, limited workflow automation, and dependence on modelling assumptions [6–8]. Empirical studies likewise indicate that the routine use of BIM-LCA remains dependent on organizational maturity, model structure, and data quality, which continues to limit its broader uptake in design workflows [9,10].

Despite the growing interest of research on WLC assessment, existing studies predominantly address technological, methodological, or policy-related aspects in isolation. While several reviews have identified barriers to embodied carbon assessment and BIM-LCA [11], limited attention has been given to the interaction between digital, regulatory, and socio-cultural factors within specific regional contexts.

Furthermore, current literature provides insufficient insight into how these barriers appear in smaller construction markets, where institutional capacity, data availability, and digital maturity remain uneven. In particular, the Baltic region represents an underexplored context, despite its relevance for EU-wide implementation of WLC requirements under the revised EPBD.

This study addresses this gap by providing a systematic and integrative analysis of WLC implementation barriers across digital, policy, and socio-cultural domains, with a specific focus on their interaction within the Baltic construction sector.

The Baltic countries represent a relevant context for examining these challenges. While European policy frameworks provide a common regulatory direction, national construction sectors may experience different conditions related to digital maturity, regulatory implementation, and market practices. As a result, the transition towards WLC assessment may encounter different types of barriers across technological, institutional, and behavioral dimensions. Understanding these barriers is important for identifying potential constraints affecting the adoption of life-cycle carbon assessment and for supporting the development of coherent policy instruments and decision-support tools.

Against this background, the objective of this study is to systematically identify, classify, and analyze digital, policy, and socio-cultural barriers affecting the implementation of Whole-Life Carbon approaches in the construction sector of the Baltic countries. By synthesizing evidence from academic literature, policy documents, and technical reports, the study aims to provide a structured understanding of the factors influencing WLC adoption and to support the development of decision-support tools and policy frameworks.

The study addresses the following research questions:

1. What digital barriers influence the implementation of WLC assessment in the construction sector?
2. How do regulatory frameworks, including EPBD, Level(s), and EN 15978, shape the adoption of WLC approaches?
3. What socio-cultural factors influence the integration of life-cycle carbon assessment into construction practices?

By addressing these questions, the study contributes to a more systemic and integrated understanding of the socio-technical transition towards WLC assessment and to identify key challenges affecting its practical implementation in the construction sector.

The contribution of this review has three main dimensions. First, it consolidates evidence on digital, policy, and socio-cultural barriers to WLC implementation, which are often addressed separately in existing literature. Second, it links these thematic barriers to the specific policy and market conditions of the Baltic States, where EU requirements are evolving, different levels of national readiness, limited empirical carbon data, and different levels of digital and institutional capacity shape WLC implementation. Third, by focusing on Estonia, Latvia, and Lithuania, the study provides insights that are relevant not only to the Baltic region but also to other smaller European construction markets facing similar challenges in translating EU-level decarbonization objectives into operational assessment methods, data infrastructures, and professional practice.

2. Conceptual background of whole-life carbon transition

WLC assessment has emerged as a central concept in the decarbonization of the built environment. Unlike traditional approaches that focus primarily on operational energy consumption, WLC evaluates greenhouse gas emissions generated throughout the entire building life cycle, including material production, construction, operation, maintenance, and end-of-life stages. This broader perspective reflects a shift in both research and policy towards life-cycle-based evaluation of environmental performance in the construction sector.

The transition towards WLC assessment is supported by advances in digital technologies, methodological frameworks, and regulatory initiatives. Digital tools such as BIM increasingly enable the integration of LCA methods within design processes, while policy frameworks such as the revised EPBD and the Level(s) framework promote life-cycle-based evaluation of buildings. At the same time, the implementation of WLC assessment involves challenges that extend beyond technological aspects, including regulatory coordination and socio-cultural factors influencing decision-making within the construction sector.

To examine these challenges, this section outlines the conceptual background of WLC implementation. It first explains the transition from operational energy assessment to whole-life carbon accounting, then discusses the role of digital tools and regulatory frameworks in enabling WLC assessment and finally considers socio-cultural factors influencing adoption. Based on these perspectives, the section introduces the analytical framework used in this study.

2.1. From operational energy to whole-life carbon

Historically, building decarbonization strategies have focused primarily on reducing operational energy consumption. However, as energy efficiency standards have improved and operational energy demand has declined, embodied emissions associated with material production, transport, construction, maintenance, and end-of-life stages have become increasingly significant [2,3].

WLC assessment expands the analytical boundary beyond operational energy use by accounting for emissions across all life-cycle stages defined in EN 15978. While embodied carbon assessments often focus on the product stage (modules A1–A3), WLC assessment also includes operational energy use (B6), replacement cycles (B2–B5), and end-of-life processes (C modules). This approach provides a more comprehensive understanding of building-related emissions and aligns performance evaluation with long-term decarbonization objectives [12,13].

The shift from operational energy metrics to whole-life carbon accounting therefore represents a broader transformation in building performance assessment. Integrating embodied and operational emissions within a single framework is increasingly recognized as necessary for achieving climate neutrality in the building sector [14].

2.2. Digital enablement of BIM–LCA integration

Digitalization plays an important role in enabling WLC assessment in the construction sector. BIM provides structured digital representations of building geometry, materials, and quantities, while LCA methodologies allow environmental impacts to be calculated using life-cycle inventory data.

The integration of BIM and LCA has been widely explored to automate quantity extraction, improve environmental assessment accuracy, and support early-stage decision-making during building design. Systematic reviews consistently identify BIM-LCA integration as a key enabler of scalable life-cycle carbon assessment, particularly for design-stage optimization and environmental performance evaluation [6,7]. BIM-based workflows allow quantity take-offs to be linked with Environmental Product Declaration datasets, enabling iterative evaluation of carbon impacts during the design process.

Despite these advantages, interoperability challenges remain significant. Industry Foundation Classes (IFC) schemas were not originally designed to represent many attributes required for life-cycle assessment, such as service lives, system boundaries, or environmental product declarations. As a result, data exchange between BIM and LCA tools may lead to semantic inconsistencies or partial information loss during export processes [6]. Empirical studies further show that different software combinations can produce different WLC results from identical BIM models due to variations in data mapping procedures and dataset selection [8].

Consequently, the level of digital maturity within the construction sector becomes an important condition for the effective implementation of WLC assessment and for meeting emerging regulatory reporting requirements.

2.3. Regulatory context of EPBD, Level(s), and WLC mandate

The regulatory framework supporting WLC implementation in Europe is increasingly shaped by recent policy developments. At EU level, the revised Energy Performance of Buildings Directive establishes a foundation for integrating life-cycle carbon considerations into building regulation. The Directive introduces mandatory calculation and disclosure of life-cycle Global Warming Potential for new buildings larger than 1000 m^2 from 2028 and for all new buildings from 2030 [12].

The Level(s) framework complements this regulatory direction by providing methodological guidance for assessing environmental performance across building life cycles. It aligns with EN 15978 principles and defines assumptions regarding life-cycle modules, reporting boundaries, and reference study periods [13]. In parallel, the revised Construction Products Regulation and the introduction of Digital Product Passports aim to improve transparency and accessibility of environmental data for construction products.

Although the European Union establishes a common direction for WLC assessment, practical implementation remains dependent on national regulatory systems. Member States are responsible for defining calculation methods, benchmarks, and implementation pathways through instruments such as National Building Renovation Plans [15]. In smaller construction markets, the limited availability of empirical WLC data may restrict the development of reliable benchmarks and delay the transition from reporting-based regulation to performance-based requirements.

2.4. Socio-cultural dimension of the transition

Technological and regulatory developments alone are insufficient to ensure the effective implementation of WLC assessment. Socio-cultural factors within the construction sector also influence the adoption of new methods and practices. These factors include professional competencies, procurement practices, institutional structures, and stakeholder attitudes towards sustainability.

Research on sustainability transitions emphasizes that technological innovation must be accompanied by behavioral and institutional change to enable systemic transformation [16]. In construction markets where cost considerations dominate decision-making, investments in low-carbon materials or additional modelling efforts may be limited unless supported by regulatory incentives or financial mechanisms [13].

In addition, competencies related to life-cycle modelling and digital workflows remain unevenly distributed across the construction sector. Small and medium-sized enterprises often face difficulties in adopting new digital tools and environmental assessment methods due to limited resources or expertise. The availability of qualified professionals therefore plays a critical role in determining the capacity of the construction sector to integrate sustainability assessment into routine practice [17].

2.5. Analytical Framework

Based on the reviewed literature, this study conceptualizes barriers to WLC implementation within three interacting domains:

- Digital barriers, including interoperability limitations, data availability issues, and automation constraints.
- Policy barriers, including methodological harmonization challenges, benchmark development, and regulatory clarity.
- Socio-cultural barriers, including skills gaps, procurement practices, and institutional inertia.

This conceptualization treats the construction sector as a socio-technical system in which technological infrastructures, regulatory frameworks, and stakeholder behavior evolve together. Within such systems, the feasibility of WLC implementation depends not on improvements within a single domain but on coordinated alignment across digital tools, policy instruments, and sectoral capabilities.

3. Methodology

3.1. Research design

This study applies to a qualitative systematic literature review combined with thematic synthesis to investigate barriers affecting the implementation of WLC approaches in the construction sector. The research design is based on established principles of systematic review methodology, ensuring transparency, consistency, and analytical rigor throughout the research process [20,21].

The objective of the study is interpretative rather than statistical. Instead of quantifying effect sizes, the analysis focuses on identifying recurring patterns, relationships, and underlying mechanisms influencing WLC implementation. This approach is particularly suitable for research domains, where empirical evidence is heterogeneous and requires conceptual and integrative synthesis rather than quantitative aggregation [22].

The review follows a structured protocol aligned with the PRISMA 2020 guidelines [20], which provide a standardized framework for documenting the processes of study identification, screening, eligibility assessment, and inclusion. The application of PRISMA ensures methodological transparency and reproducibility of the literature selection process.

The overall methodological approach combines systematic identification of relevant academic literature with qualitative thematic analysis. This enables the integration of insights from both scientific publications and supporting contextual sources, facilitating a comprehensive understanding of the technological, regulatory, and socio-cultural factors influencing WLC implementation in the construction sector.

The research design is therefore grounded in a socio-technical perspective, recognizing that the adoption of WLC assessment is shaped not only by methodological and digital capabilities, but also by policy frameworks, institutional conditions, and stakeholder practices.

3.2. Search strategy and literature selection

Peer-reviewed publications were identified through structured searches in major academic databases commonly used in built environment research, including Web of Science and Scopus, accessed via platforms such as ScienceDirect and other publisher databases.

The search focused on publications published between 2018 and 2025, reflecting the period during which Whole-Life Carbon assessment gained increasing attention in both academic research and European policy development.

Search queries were developed to capture studies addressing life-cycle carbon assessment, digitalization in construction, and regulatory frameworks. The search strategy combined keywords such as “whole-life carbon” OR “embodied carbon” with “BIM” AND “life-cycle assessment” AND “construction”, ensuring coverage of both methodological developments and implementation challenges. Additional terms included “construction decarbonization” and “EPBD implementation” to capture policy-related aspects.

The geographical focus was applied through a two-level evidence strategy. First, peer-reviewed literature was selected to identify general WLC, BIM-LCA, regulatory, and socio-cultural implementation barriers relevant to the construction sector. This search was not restricted only to Baltic publications, because many barriers affecting WLC implementation are discussed in broader European and international literature. Second, Baltic relevance was established through targeted consideration of studies and policy/institutional documents referring to Estonia, Latvia, Lithuania, or comparable small European construction markets. Of the 58 peer-reviewed studies included in the systematic review, 4 specifically focused on the Baltic region (Estonia, Latvia, or Lithuania). These studies were complemented by 16 policy and institutional documents, which were analysed separately to contextualize the identified barriers within the Baltic regulatory, institutional, and market environment. Evidence selection strategy and role of source groups in the Baltic-focused synthesis are presented in Table 1.

The initial search returned 512 records. After removing duplicates, 438 records remained for title and abstract screening. Studies not directly related to WLC assessment, BIM-LCA integration, or construction-sector decarbonization were excluded at this stage. A total of 126 articles were selected for full-text review. Following full-text assessment, 58 peer-reviewed publications were included in the final systematic review.

Table 1
Evidence selection strategy and role of source groups in the Baltic-focused synthesis.

Source group	Selection focus	Role in the review
Peer-reviewed WLC and embodied carbon studies	Studies addressing WLC, embodied carbon, LCA methods, and implementation barriers in construction	Identified general methodological and implementation barriers
Peer-reviewed BIM–LCA studies	Studies addressing BIM–LCA integration, interoperability, data exchange, and workflow automation	Supported the digital barrier synthesis
Policy and regulatory sources	EPBD, Level(s), EN 15978, BPIE, BUILD UP, and related EU-level sources	Defined the regulatory framework for WLC implementation
Baltic national documents	Estonian, Latvian, and Lithuanian renovation, energy, climate, and building-policy documents	Contextualized how EU-level requirements are translated into national settings
Baltic or small-market evidence	Studies or reports referring to Estonia, Latvia, Lithuania, or comparable small construction markets	Supported regional interpretation and generalizability beyond the Baltic case

In addition to database searches, backward and forward citation tracking was applied to complement the search strategy and identify additional relevant publications referenced in key studies [20].

Alongside the systematic literature review, 16 policy and institutional documents were identified separately and analysed to contextualize regulatory frameworks and implementation conditions of WLC assessment. These sources were not included in the PRISMA selection process but contributed to the broader analytical framework of the study.

3.3. Policy and institutional sources

In addition to the systematic review of academic literature, the study incorporates policy and institutional documents to provide context for the regulatory and implementation environment of WLC assessment in Europe. These sources were identified separately from the database search and were not included in the PRISMA-based selection process.

The analysis focuses on key European-level frameworks shaping the adoption of life-cycle carbon assessment in the built environment. These include Directive (EU) 2024/1275 on the Energy Performance of Buildings, the Level(s) framework for sustainable buildings, and the EN 15978 standard for life-cycle assessment of buildings. Supporting materials published by the European Commission, the BUILD UP platform, and the Buildings Performance Institute Europe (BPIE) were also reviewed to capture recent developments in policy implementation and methodological harmonization.

To complement the European perspective, national strategic documents from the Baltic region were examined. These include National Long-Term Renovation Strategies (LTRS), National Energy and Climate Plans (NECP), and National Building Renovation Plans (NBRPs) of Estonia, Latvia, and Lithuania. These documents provide insight into how WLC-related principles are translated into national policies and implementation practices.

A total of 16 policies and institutional sources were analysed. While not part of the systematic literature review, these documents contribute to the broader interpretative framework of the study, supporting the analysis of policy-related barriers and enabling a more comprehensive understanding of the socio-technical context of WLC implementation.

3.4. Inclusion and exclusion criteria for study selection

Inclusion and exclusion criteria were defined prior to the screening process to ensure consistency and analytical relevance of the selected literature. Studies were included if they addressed methodological aspects of WLC or embodied carbon assessment, the integration of BIM and LCA, regulatory frameworks influencing life-cycle carbon calculation, or implementation barriers related to decarbonization in the construction sector.

Studies were excluded if they focused on sectors unrelated to the built environment, lacked analytical or methodological depth, or addressed environmental assessment without a clear connection to life-cycle carbon. In addition, sources outside the European policy and regulatory context relevant to WLC implementation were not considered, in order to maintain consistency with the geographical scope of the study.

The screening process was conducted in two stages. First, titles and abstracts were reviewed to assess their relevance to the research objectives. Publications meeting the inclusion criteria were subsequently evaluated through full-text review, following the structured procedures outlined in the PRISMA 2020 guidelines [20].

The inclusion and exclusion criteria were applied consistently throughout both screening stages. To ensure analytical focus, only studies explicitly addressing implementation challenges, methodological developments, or regulatory aspects of WLC assessment were retained for the final synthesis.

3.5. Study selection process

The study selection process followed the PRISMA 2020 framework, ensuring a transparent and structured approach to identifying, screening, and selecting relevant studies [20]. The procedure comprised four main stages: identification, screening, eligibility assessment, and inclusion.

Records were identified through structured database searches in Web of Science and Scopus, yielding a total of 512 records. After the removal of duplicates (n = 74), 438 records remained for title and abstract screening. At this stage, 312 records were excluded due to lack of relevance to Whole-Life Carbon assessment, BIM-LCA integration, or construction-sector decarbonization.

The remaining 126 records were assessed for full-text eligibility. Of these, 9 reports were not retrieved, resulting in 117 full-text papers evaluated. Following eligibility assessment, 59 studies were excluded based on predefined criteria, including lack of relevance to WLC implementation (n = 24), focus outside the construction sector (n = 18), and insufficient analytical relevance (n = 17).

Consequently, 58 peer-reviewed studies were included in the systematic review and formed the basis for the PRISMA-based synthesis.

In addition, 16 policy and institutional sources were identified separately and analysed to provide contextual insight into regulatory frameworks, methodological approaches, and socio-technical dimensions of Whole-Life Carbon implementation. These sources were not included in the PRISMA selection process but were incorporated into the broader thematic analysis.

The study selection procedure is illustrated in the PRISMA flow diagram presented in Fig. 1.

This structured approach enhances transparency, reduces selection bias, and strengthens the reproducibility and reliability of the review findings.

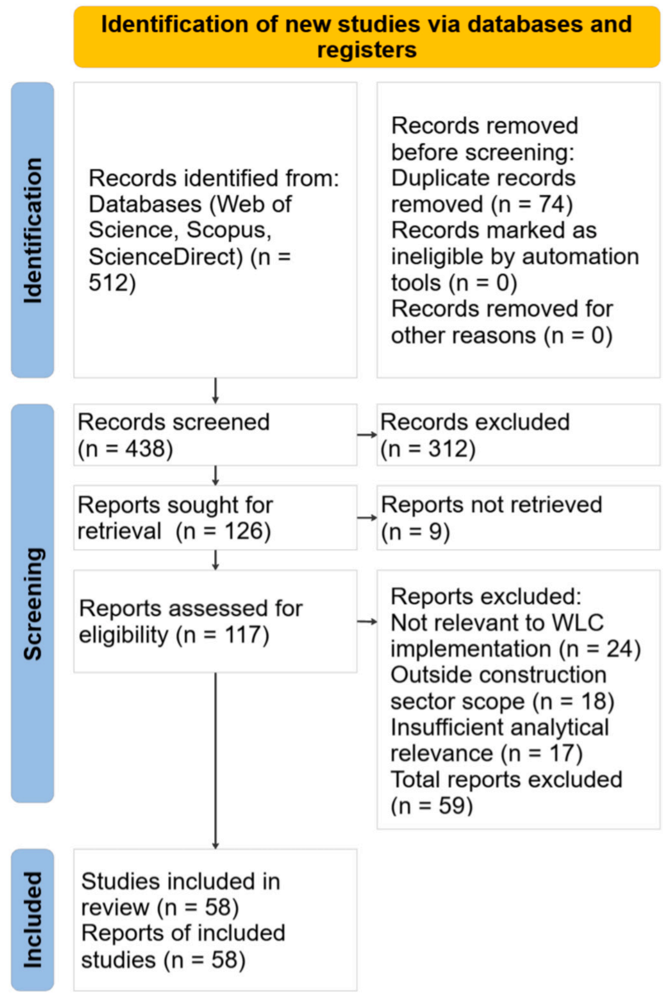

Fig. 1. PRISMA 2020 flow diagram illustrates the study selection process for the systematic review of digital, policy, and socio-cultural barriers to Whole-Life Carbon implementation [20].

3.6. Thematic analysis

The selected literature and policy documents were analysed using qualitative thematic analysis. The coding process followed a structured multi-stage procedure [23]. Initially, open coding was applied to identify recurring concepts and patterns related to WLC implementation challenges across the reviewed sources. Subsequently, the identified codes were grouped into higher-level categories reflecting broader dimensions of WLC implementation. Finally, axial coding was used to examine relationships between these categories, enabling the identification of cross-domain interactions and systemic constraints.

To link literature-based barriers with regional implementation conditions, academic sources were first coded according to the three thematic domains: digital, policy, and socio-cultural. These themes were then compared with EU and Baltic policy and institutional documents to distinguish barriers widely reported in the WLC literature from those amplified by Baltic-specific regulatory, data, digital, or market conditions. Policy documents were therefore used not only as background sources but also to interpret how general WLC barriers are manifested in national implementation settings.

The analysis was iterative, with themes continuously refined through comparison across sources. The integration of both academic literature and policy documents ensured consistency between theoretical perspectives and the regulatory context, supporting the development of an integrative analytical framework.

Attention was given to observations that appeared repeatedly across different groups of studies. For example, publications discussing BIM-LCA interoperability frequently also reported challenges related to reporting consistency, benchmark development, and the implementation of regulatory requirements. Similarly, studies examining professional competencies and organizational practices often highlighted difficulties associated with the practical application of digital assessment tools and life-cycle carbon methodologies. These recurring observations were compared across the three thematic domains and used to identify relationships between digital, policy, and socio-cultural barriers.

The analysis resulted in the identification of three dominant groups of barriers: digital barriers associated with BIM-LCA interoperability, data availability, and workflow automation; policy barriers related to regulatory implementation, benchmark development, and methodological harmonization; and socio-cultural barriers linked to professional competencies, procurement practices, and institutional inertia.

This classification reflects a broader socio-technical perspective, emphasising the interaction between technological systems, regulatory frameworks, and stakeholder behavior in sustainability transitions [24].

3.7. Analytical approach and limitations

The study adopts an interpretative synthesis approach and does not seek to quantify the relative importance of individual barriers. Instead, the analysis focuses on identifying patterns, relationships, and interactions influencing WLC implementation. While this approach enables a comprehensive understanding of complex socio-technical systems, it does not allow for statistical generalization. The findings should therefore be interpreted as analytically grounded insights derived from systematically reviewed literature rather than as empirically measured effects.

4. Results

4.1. Digital barriers to whole-life carbon implementation

Barrier 1. Role of digitalization in WLC assessment.

Effective WLC assessment depends on consistent methods, reliable data, and interoperable workflows. Digitalization is a key enabler of WLC assessment because it allows building information, environmental datasets, and performance calculations to be connected across project stages [25–28].

Building Information Modelling plays a central role in this process because it provides a structured representation of building geometry, materials, and quantities [8]. BIM-based Life Cycle Assessment workflows can support early-stage performance feedback and help designers compare options before construction begins [29–32]. This is particularly important because early design decisions strongly influence life-cycle carbon outcomes.

With the increasing relevance of life-cycle assessment in the evaluation of building performance, modern energy simulation tools are beginning to incorporate material databases and export functionalities that enable coupling with LCA frameworks. This allows the assessment of embodied impacts alongside operational energy use within a single modelling environment. For example, simulation tools are increasingly incorporating their capabilities to support integration with life-cycle assessment workflows [31,33].

At the same time, the practical value of BIM-LCA workflows is reduced by persistent problems in data mapping, model consistency, and interoperability [6]. In practice, assessments often require manual adjustments, especially for elements such as foundations, facades, partitions, railings, windows, and doors [34]. The need to combine separate discipline-specific models further increases the time required for data preparation and raises the risk of inconsistencies [34]. As a result, accurate bills of quantities, correct unit conversions, and appropriate dataset assignments remain essential but are not yet fully automated [34].

Many WLC studies still rely on simplified or semi-manual calculation approaches. This is increasingly problematic because regulatory frameworks such as the revised EPBD and the EU Level(s) framework require more standardized and repeatable approaches to whole-life carbon assessment [35].

Barrier 2. Limitations of BIM-LCA interoperability.

Despite growing interest in BIM-LCA integration, interoperability remains a major barrier to consistent and scalable WLC assessment. Current approaches often rely on proprietary plugins, software-specific workflows, or intermediate file exports to LCA tools [6]. While these approaches allow quantity extraction, they frequently lack transparency, reproducibility, and robustness.

A key limitation is that open data standards such as IFC were not originally developed to support life-cycle assessment requirements. As a result, critical parameters such as service life, system boundaries, and environmental indicators are either missing or only partially represented [36]. This structural mismatch leads to information loss during model exchange, requiring manual correction and reducing workflow automation [8,36,37].

Importantly, this limitation has systemic implications. It reduces the reproducibility and comparability of WLC results across projects and software environments. Consequently, interoperability challenges do not only affect technical workflows but also undermine the reliability of WLC assessment as a basis for regulatory reporting and benchmarking.

This problem is reinforced by dependence on proprietary software environments. The same BIM model may produce different WLC assessment results depending on the software combination, mapping logic, and datasets used [38,39]. Such variation weakens comparability across projects and complicates the development of consistent reporting and benchmarking practices.

Interoperability challenges also increase when multiple discipline-specific models need to be combined before assessment. Architectural, structural, and MEP models often require additional consolidation, interpretation, and unit conversion before meaningful WLC results can be obtained [34]. For this reason, BIM-LCA workflows remain difficult to scale from project-level analysis to broader stock-level or policy-oriented applications [39].

Although standardized LCA schemas and improved data exchange protocols are emerging, they are not yet widely adopted [36,38]. Until interoperability improves, BIM-LCA workflows will remain limited in terms of reproducibility, comparability, and routine use in design practice.

These findings indicate that interoperability limitations do not function as isolated technical issues but as systemic constraints that affect the reliability, comparability, and scalability of WLC assessment. Inconsistent data exchange reduces confidence in results and limits their usability for regulatory reporting and benchmarking.

Therefore, digital barriers directly constrain the operationalization of policy requirements, particularly those introduced by the revised EPBD, which rely on standardized and reproducible life-cycle carbon calculations.

Barrier 3. Data structure and modelling inconsistencies in BIM models.

BIM models are typically developed for design coordination and construction documentation rather than for WLC assessment. As a result, material definitions and layer compositions are often incomplete or oversimplified, especially for elements such as foundations, facades, partitions, railings, windows, and doors [34].

These issues become more pronounced when models are prepared by different stakeholders. Variations in naming conventions, classification systems, and object development levels make automated extraction more difficult and reduce the reliability of WLC calculations [34]. In smaller construction markets, lower BIM maturity can further increase heterogeneity in modelling practice and complicated benchmarking and early-stage assessment [7].

Another problem is that design changes at later project stages can invalidate previously completed LCA calculations [8]. When geometry, materials, or system compositions change, these modifications are not always propagated automatically through existing workflows, which creates additional manual work and lowers confidence in the results.

The feasibility of extracting data from BIM models for WLC assessment depends strongly on model structure and computational requirements [33,40,41]. Some performance models require only basic dimensional information, whereas others rely on more detailed geometric or component-level data. This means that modelling consistency directly affects the reliability of WLC outputs.

Overall, inconsistencies in model structure reduce the accuracy, reproducibility, and comparability of WLC assessment results. Digitalization alone does not solve these problems without more standardized modelling practices, clearer naming conventions, and more consistent material definitions [7].

Barrier 4. Data availability and quality constraints.

Reliable life-cycle inventory data is essential for credible WLC assessment [8]. However, in the Baltic context, regional and national LCA databases remain limited, which often forces practitioners to rely on generic or international datasets and increase uncertainty in the results [42].

Additional difficulties arise from inconsistencies in Environmental Product Declarations. Differences in system boundaries, declared units, and covered life-cycle stages make dataset selection and comparison more difficult [37]. Without sufficiently consistent and representative LCI data, WLC results may fail to reflect actual environmental impacts.

Digital Product Passports may improve data traceability and product-level environmental transparency by linking information directly to BIM-based workflows. However, current implementation remains limited, which creates a gap between the expected benefits of digital data systems and their practical use in WLC assessment [43].

These data limitations introduce a significant level of uncertainty into WLC calculations, particularly when generic datasets are used as proxies for local construction practices. As a result, the accuracy of carbon assessments becomes dependent not only on modelling precision but also on the representativeness of underlying datasets. This creates a structural constraint for benchmarking and policy implementation, where reliable and comparable data are essential.

Barrier 5. Limited automation and fragmented digital tool ecosystems.

Although BIM-LCA workflows offer some potential for automation, current tools still require substantial manual effort for quantity mapping, data matching, and dataset assignment [38]. The absence of real-time feedback also restricts iterative optimization and reduces the usefulness of these workflows during early design stages.

A related challenge is the fragmented nature of the digital tool ecosystem. Most tools address only isolated parts of the workflow, such as monitoring, simulation, or specific material-related tasks, rather than providing integrated support across disciplines and project stages [44–48]. This fragmentation limits the scalability of WLC implementation and makes standardized benchmarking more difficult.

Integration with EPC systems, national reporting frameworks, and building registries also remains limited. This restricts the possibility of aggregating results at building stock level and reduces the policy relevance of digital carbon assessments. Additional challenges arise from semantic reasoning and automation-related processes, which require alignment of ontologies, rules, and computational logic [49–51].

Existing digital solutions can reduce remodeling effort and improve feedback loops, but they still rarely provide holistic decision support for WLC-oriented design [49,52–54]. Taken together, low automation and fragmented digital ecosystems remain major barriers to scalable and policy-compliant WLC implementation.

4.2. Policy barriers

4.2.1. Current state of EU WLC regulations

At the EU level, several policy initiatives aim to accelerate the transition towards a decarbonized built environment based on sustainability, circularity, and whole-life thinking. The European Green Deal establishes the strategic direction towards climate neutrality by 2050 and supports subsequent regulatory initiatives relevant to the construction sector, including the Level(s) framework, the Circular Economy Action Plan, the EU Taxonomy, the Renovation Wave, the EU Climate Law, and the revised EPBD [14].

The recast Energy Performance of Buildings Directive (Directive (EU) 2024/1275) significantly strengthens the EU framework for decarbonizing the building sector and introduces new requirements related to whole-life carbon. A central instrument of the revised Directive is the introduction of NBRPs, which replace the earlier Long-Term Renovation Strategies previously submitted by Member States. These plans define national pathways towards a highly energy-efficient and decarbonized building stock by 2050 and prioritize the renovation of the worst-performing buildings as part of the EU Renovation Wave [15].

Under the revised EPBD, Member States must establish indicative national targets for 2030, 2040, and 2050 supported by policy measures and investment strategies. For non-residential buildings, Member States must ensure renovation of at least 16% of the worst-performing buildings by 2030 and 26% by 2033. For residential buildings, the Directive requires a reduction in the average primary energy consumption of at least 16% by 2030 and 20–22% by 2035 compared with 2020 levels [12,55].

A key innovation of the revised EPBD is the introduction of mandatory whole-life carbon reporting for new buildings. From 2028, life-cycle global warming potential (GWP) must be calculated for all new buildings larger than 1000 m^2, and from 2030 this requirement will apply to all new buildings. Member States must therefore develop national methodologies, reporting systems, and data infrastructures to support life-cycle carbon disclosure [12,55].

The Directive also strengthens Energy Performance Certificate (EPC) systems. By 2026, Member States must adopt EPC schemes to include additional indicators related to energy use and greenhouse-gas emissions, improving comparability and transparency across the EU building stock [12,55].

Another important regulatory component is the Construction Products Regulation (CPR). While the EPBD addresses building-level performance, CPR regulates environmental information at the product level. Together with the Ecodesign for Sustainable Products Regulation, the revised CPR introduces DPPs, requiring manufacturers to provide environmental data for construction products. These datasets are expected to support more reliable WLC assessments in the future [13].

4.2.2. Current state of WLC regulations in Baltic countries

Energy and carbon metrics address complementary aspects of building decarbonization. Energy indicators typically focus on operational performance, while whole-life carbon assessment captures both operational and embodied emissions. National renovation strategies prepared around 2020 provided an analytical basis for the EU Renovation Wave and informed the development of the recast EPBD [18,19].

Within this framework, Estonia, Latvia, and Lithuania have defined indicative renovation pathways, energy-saving targets, and emission-reduction trajectories for their building sectors. These targets are summarized in Tables 2–4.

The Baltic comparison shows that WLC readiness depends on the alignment of digital maturity, policy readiness, and institutional capacity. Estonia demonstrates how early national tools and datasets can support implementation learning, Latvia shows that energy-efficiency institutions do not automatically translate into WLC regulation, and Lithuania illustrates the limits of voluntary/project-based LCA for creating benchmarks. This suggests that other small European markets may face similar difficulties if EU-level WLC requirements are introduced faster than national data systems, administrative procedures, and professional competencies can develop.

4.2.2.1. Estonia. In Estonia, the Ministry of Climate coordinates the preparation of the NBRP in cooperation with government agencies, research institutions, and sector organizations. Key stakeholders include the Estonian Energy Efficiency Centre of Excellence, Tallinn University of Technology, and construction sector associations [56].

Estonia's energy and climate policy framework is largely defined

Table 2
Indicative renovation coverage of the building stock in the Baltic countries (LTRS-based) [18].

Country	Reference year	2030	2040	2050
Estonia	2020	22% of the total building stock renovated	64% of the total building stock renovated	Renovation of nearly all buildings constructed before 2000
Latvia	2020	30% of multi-apartment buildings (≈4860 buildings); 500,000 m^2 of public buildings	8100 multi-apartment buildings; 3% annually of the central government building floor area	All new buildings meet the NZEB requirements
Lithuania	2021	17% of the total building stock renovated	43% of the total building stock renovated	74% of the total building stock renovated

Table 3
Indicative energy savings in the building sector (LTRS scenarios) [19].

Country	Reference year	Energy metric	Baseline (ktoe)	2030	2040	2050
Estonia	2020	Final energy consumption (FEC)	1006	n/d	n/d	−59%
Latvia	2018	Final energy consumption (FEC)	1910	−23%	n/d	n/d
Lithuania	2020	Primary energy consumption (PEC)	3510	−15%	−37%	−60%

Table 4
Indicative greenhouse gas emission reductions in the building sector (LTRS scenarios) [19].

Country	Reference year	Baseline emissions (Mt CO_2e)	2030	2040	2050
Estonia	2020	4.43	n/d	n/d	−89%
Latvia	2017	2.77	−8%	n/d	n/d
Lithuania	2020	5.29	−24%	−60%	−100%

through the National Energy and Climate Plan (NECP 2030), which consolidates several national strategies addressing climate policy, energy development, and climate adaptation [57]. Within the building sector, the NECP focuses primarily on renovation of public, commercial, and residential buildings and on the implementation of nearly zero-energy building (NZEB) requirements.

Estonia's Long-Term Renovation Strategy (LTRS) aims to achieve cost-effective renovation of the entire building stock, particularly buildings constructed before 2000, and to reach NZEB performance levels by 2050 [58]. Priority measures include envelope insulation, window replacement, heating system upgrades, and building automation technologies [65,69].

To support carbon assessment, Estonia has introduced national calculation tools such as the SARV building carbon footprint calculator developed by Tallinn University of Technology. The tool enables building-level carbon calculations and uses the Estonian Material Emission Factor Database (EHEA), which provides emission factors for commonly used construction materials. Two calculation approaches are available: 1) based on cradle-to-gate emissions (A1-A3) and 2) aligned with the Level(s) framework that includes biogenic emissions [59].

However, the use of SARV and EHEA should be interpreted with methodological caution. EHEA provides national emission factors intended to represent typical Estonian construction-material conditions and to support carbon footprint assessment of construction works, but its coverage is not equivalent to a complete product-specific EPD database. Uncertainty may arise from the use of generic or average emission factors, differences in data age, production technologies, system boundaries, declared units, and assumptions regarding biogenic carbon or life-cycle modules. Therefore, EHEA can improve national representativeness compared with foreign generic datasets, but results may not always be directly comparable with international EPD-based assessments unless harmonized boundaries, units, calculation rules, and EN 15804/EN 15978 assumptions are applied.

4.2.2.2. Latvia. Latvia has established a regulatory framework supporting building energy efficiency through the Law on the Energy Performance of Buildings and several Cabinet Regulations governing energy certification, calculation methods, and thermal performance requirements [60,61].

Energy certification has been implemented since 2013, supported by the National Construction Information System, which maintains registers of Energy Performance Certificates and certified experts. NZEB requirements have applied to all new public buildings since 2019 and to all new buildings since 2021 [60,61].

According to Latvia's LTRS, the country aims to significantly reduce building-sector emissions by 2050 through deep renovation and improved energy performance of new buildings. Scenario modelling suggests that emissions could decrease by up to 80% if additional energy savings are achieved through renovation programmes [18,62].

Despite these policy efforts, Latvia continues to face structural challenges related to housing conditions and energy poverty. Limited financial capacity of property owners and restricted access to financing remain barriers to large-scale renovation. Although financial instruments such as loans, tax incentives, and municipal support schemes are available, WLC assessment is not yet regulated at the national level and is typically performed only on a voluntary or project-specific basis.

4.2.2.3. Lithuania. In Lithuania, the Ministry of Environment coordinates the preparation of the NBRP and previously supervised the development of the Long-Term Renovation Strategy. Implementation involves multiple institutions, including the Public Investment Development Agency, the Lithuanian Energy Agency, and municipal authorities [56].

Lithuania's regulatory framework includes the Law on Construction and national technical regulations on building energy performance. NZEB corresponds to energy performance class A++, which has been mandatory for all new buildings since 2021 [18,63].

The national renovation strategy aims to decarbonize the building stock by 2050. Achieving this objective will require renovation of approximately 74% of the existing building stock, significant reductions in primary energy consumption, and a gradual phase-out of fossil fuels in buildings. These challenges are intensified by the age structure of the building stock, as a large proportion of buildings were constructed before 1992 and exhibit low energy performance [18,63].

At present, whole-life carbon assessment is not regulated at the national level. Where life-cycle assessments are performed, they typically follow international standards such as EN 15978 or voluntary sustainability frameworks such as the Lithuanian Building Sustainability Evaluation System developed by the Lithuanian Green Building Council [64,65].

A comparison of Baltic countries reveals differentiated levels of readiness for WLC implementation. Estonia demonstrates a more advanced stage through the development of national carbon assessment tools and datasets, while Latvia shows partial institutional readiness but lacks regulatory integration of WLC assessment. Lithuania remains at an earlier stage, where life-cycle carbon assessment is primarily voluntary and project-specific.

These differences indicate that the transition towards mandatory WLC reporting under the EPBD will likely follow uneven trajectories across the region, requiring country-specific policy support and capacity-building strategies.

4.2.3. Policy barriers for WLC implementation

According to the BPIE report (2025), WLC policy development consists of two key components: the definition of methodologies and data requirements, and the establishment of regulatory pathways and performance targets [13]. Although EN 15978 defines general principles for building life-cycle assessment, practical implementation across EU Member States remains uneven.

Barrier 1. Inconsistencies in assessment methodologies and scope.

WLC assessment methods define spatial boundaries, including building elements, life-cycle stages, assumed service life, and reference floor area. While emissions from material production (A1-A3) are typically included in all Baltic countries, later life-cycle stages such as construction processes, replacement cycles, and end-of-life scenarios are often treated differently. These variations result from differences in national practices, regulatory priorities, and data availability.

The Baltic countries are also at different stages of WLC implementation. Estonia has developed national tools and pilot projects, whereas Latvia and Lithuania currently rely mainly on voluntary or project-specific assessments. This uneven readiness may complicate the introduction of mandatory WLC disclosure under the revised EPBD.

Another source of divergence is the definition of NZEBs and worst-performing buildings. Estonia commonly identifies inefficient buildings based on construction period, Latvia uses energy-consumption thresholds, and Lithuania applies energy-performance classes. Such differences complicate cross-country comparison and may hinder regional benchmarking under future EPBD monitoring mechanisms.

Barrier 2. Data availability and quality.

Reliable WLC assessment requires carbon data for all materials included in the building bill of quantities. In practice, assessments often combine product-specific Environmental Product Declarations with generic datasets. From 2026 onwards, Digital Product Passports are expected to improve data transparency, but a transition period with continued reliance on generic data is likely [13].

Because national databases remain limited in several Baltic countries, practitioners frequently use foreign EPD datasets. While data from neighboring or Nordic countries may provide a reasonable approximation due to similar construction practices, differences in geographical conditions and manufacturing technologies may still affect accuracy.

Barrier 3. Limited empirical data for benchmark setting.

WLC regulation typically develops through a stepwise process. Initial phases focus on data collection and voluntary reporting, which creates a statistical basis for defining benchmarks. Once sufficient data is available, policymakers can introduce limit values and emission-reduction targets [13].

In smaller construction markets such as the Baltic States, the relatively low number of WLC assessments slows the creation of representative datasets. This may delay the transition from disclosure-based regulation to performance-based carbon limits.

Barrier 4. Fragmented LCA tool landscape.

Another challenge relates to the diversity of LCA calculation tools used by practitioners. Tools are developed by public institutions, research organizations, NGOs, and private companies, and they often follow different calculation assumptions or datasets. As WLC regulation expands, ensuring compliance of these tools with national and EU methodologies becomes increasingly important.

Quality assurance mechanisms may include approved tool lists, methodological validation, or third-party verification procedures based on EN 15978 or related standards [13].

Barrier 5. Integration with EPC systems.

The recast EPBD requires life-cycle carbon information for new buildings to be disclosed through Energy Performance Certificates. This requirement creates a need to integrate WLC calculation methodologies with existing EPC frameworks.

Although many input parameters overlap between EPC calculations and WLC assessments, national EPC systems currently differ across the Baltic countries. Adapting these systems to include carbon indicators will require institutional coordination and technical adjustments.

Barrier 6. Skills, market readiness and stakeholder engagement.

Effective implementation of WLC policies depends on the availability of qualified professionals and the readiness of the construction sector to adopt life-cycle assessment methods. Many practitioners still have limited experience with WLC calculations, and additional training, guidance, and technical support are required.

Collaboration between public authorities, industry, and academia can help identify skills gaps and develop targeted training programmes. Public construction projects can also play a leading role by demonstrating WLC assessment methods and supporting broader market adoption.

Taken together, these barriers indicate that policy challenges are not limited to regulatory absence but are primarily related to inconsistencies in implementation, data infrastructure, and methodological harmonization. In particular, the lack of aligned calculation approaches across countries weakens comparability and slows the transition from voluntary reporting to enforceable carbon limits. This suggests that the effectiveness of WLC policy depends not only on regulatory ambition but also on the coherence of supporting technical and institutional systems.

4.3. *Socio-cultural barriers*

While substantial research has examined environmental and economic aspects of sustainable construction, the social dimension remains comparatively underexplored. Existing literature frequently highlights knowledge gaps related to stakeholder participation, community engagement, and the distribution of benefits associated with sustainability transitions [66]. Knowledge, values, and behavioral patterns are increasingly recognized as important determinants of sustainability transformation processes [17]. In the context of building decarbonization, cultural and demographic factors can influence occupants' behavior and acceptance of new construction practices, yet these aspects remain insufficiently addressed in many studies [67].

Although retrofit programmes and building decarbonization policies are often designed primarily from technical and financial perspectives, their effectiveness ultimately depends on the individuals and communities affected by them. Building interventions influence health, comfort, productivity, and social equity outcomes [68]. As a result, occupants' behavior, socioeconomic conditions, and institutional trust play an important role in determining the success of building decarbonization strategies [69].

Recent market evidence suggests that sustainability considerations are gradually gaining importance in the Baltic real estate sector. According to the Baltic Real Estate Market Outlook 2025, demand for energy-efficient office and industrial buildings has increased, reflecting a growing recognition of sustainability-related investment risks and opportunities. However, sustainability in construction is still often interpreted narrowly in terms of energy efficiency rather than broader life-cycle environmental performance [70].

Barrier 1. Competencies and knowledge.

Stakeholders across the construction value chain, including engineers, contractors, consultants, developers, and building users, all influence how sustainability challenges are addressed in the built environment (Fig. 2) [71]. Over the past decade, climate-related responsibility has become more visible among real estate developers and construction firms, reflecting the growing pressure on the sector to respond to environmental challenges [72]. Even so, the wider circulation of knowledge and good practice remains limited.

One of the persistent difficulties is that expertise is often retained within individual organizations rather than shared across the sector. Competitive pressures may discourage collaboration, which in turn slows the broader diffusion of sustainability-oriented innovation [16]. Closer cooperation between policymakers, universities, and industry could help establish clearer guidance, improve transparency, and strengthen the practical uptake of sustainable construction approaches.

A further challenge lies in the uneven relationship between academic knowledge and industry needs. Research often focuses on environmental and social outcomes, whereas construction firms and developers tend to prioritize economic feasibility, implementation risk, and short-term project constraints. This difference in priorities can weaken the transfer of knowledge from research into practice.

Education and professional training are therefore not peripheral issues but an essential part of the transition. Public awareness and citizenship education contribute to broader understanding of environmental responsibility [73], while sector-specific training determines whether new methods can be applied in everyday construction practice. This is particularly relevant for digital and LC based approaches, which require not only technical knowledge but also familiarity with structured information management and interdisciplinary

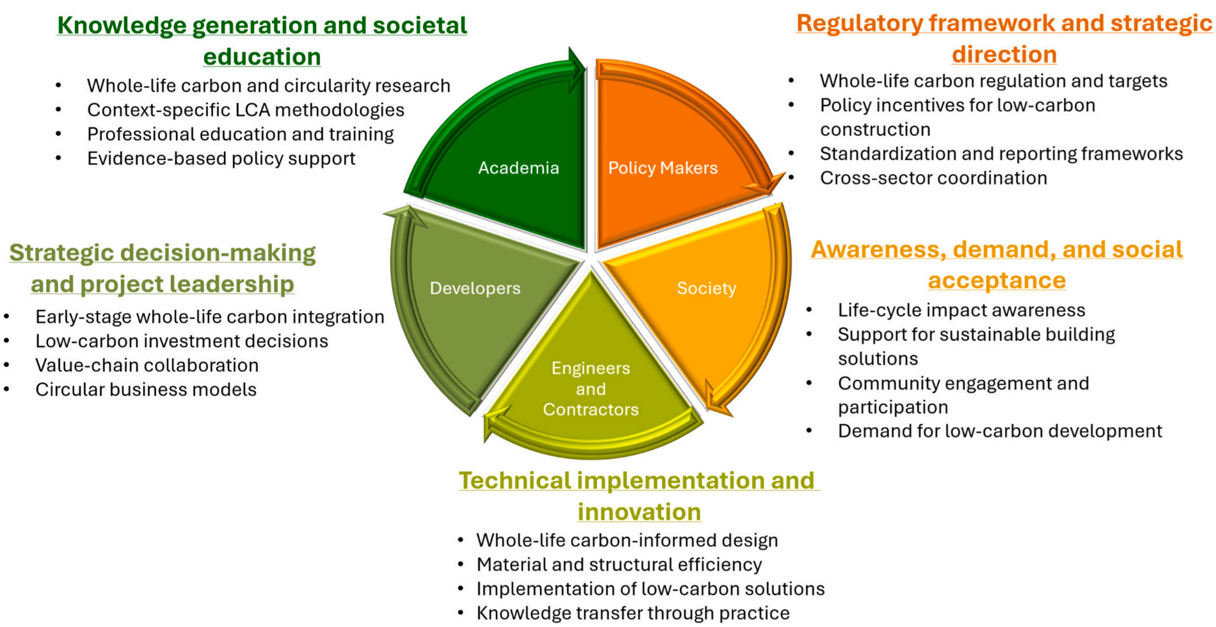

Fig. 2. Stakeholder responsibility matrix illustrates the roles of key actor groups in supporting whole-life carbon implementation through knowledge generation, strategic decision-making, technical implementation, regulatory direction, and social acceptance [68,71].

workflows [74]. In this sense, educational capacity directly affects implementation capacity.

The availability of qualified professionals remains a decisive factor. The ability of firms to adopt digital tools, develop innovative solutions, and integrate sustainability assessment into project delivery depends on workforce skills and institutional learning [75]. Where such competencies are weak or unevenly distributed, the transition towards whole-life carbon assessment is likely to remain fragmented and slow.

Barrier 2. Market resistance.

Market resistance remains one of the main obstacles to the wider adoption of low-carbon construction practices. In many cases, decisions in the construction sector are still shaped primarily by financial considerations, and sustainability measures tend to gain attention only when they are associated with clear economic returns or improved market position [66]. Under these conditions, short-term performance often outweighs longer-term environmental and social value.

Although many investors acknowledge that sustainability may strengthen long-term asset value, this recognition is still frequently limited to energy efficiency measures rather than broader life-cycle carbon reduction strategies [72]. In speculative development projects, pressure to minimize initial construction costs often leaves little room for solutions whose benefits become visible only over a longer time horizon.

This tension is also evident in renovation decisions. Higher upfront investment can improve long-term energy performance and reduce life-cycle carbon emissions [76], yet projects with shorter payback periods are still commonly regarded as the safer option. As a result, investment logic often remains conservative, even where low-carbon alternatives may be more advantageous over the building life cycle.

A similar contradiction appears in the case of material reuse. Reuse can lower greenhouse-gas emissions, reduce pressure on natural resources, and generate value across the supply chain [77]. Even so, these benefits are not always enough to shift practice, especially where the market continues to favor familiar materials, standardized solutions, and predictable short-term costs.

Social attitudes and public expectations also influence market demand. Research on public perceptions of green lifestyles and eco-friendly buildings suggests that decision-making is affected not only by environmental awareness but also by how sustainability is understood, valued, and prioritized in everyday life [78]. In Lithuania, for example, climate-related concerns often remain secondary to energy affordability [79]. A similar pattern can be observed in Estonia, where environmental considerations play a relatively limited role in major purchasing decisions [80]. In Latvia, awareness of renovation benefits also remains uneven, with many residents still insufficiently informed about the practical value of building renovation [81].

Material preferences reveal another dimension of market resistance. Although timber construction offers considerable potential for emissions reduction, mineral-based materials such as concrete and steel continue to dominate the sector. In Latvia, for example, a large share of harvested timber is exported rather than used domestically in bio-based construction, which weakens the potential for local low-carbon value creation [82]. Bio-based materials also continue to face skepticism among industry actors, particularly where they are associated with unfamiliar techniques, additional costs, or uncertainty about long-term performance [16].

Taken together, these factors suggest that market resistance is not simply a matter of cost. It is shaped by investment habits, perceived risk, public awareness, and the persistence of familiar material and procurement choices.

Barrier 3. Institutional inertia.

Institutional inertia remains a significant obstacle to the broader adoption of low-carbon construction practices. Even where sustainability objectives are formally recognized, implementation often continues to rely on established regulatory routines, familiar procurement models, and conventional construction choices [83]. This slows the transition from policy ambition to consistent practice.

In the housing and construction sectors, responsibilities are often divided between public authorities and private developers. Governments define regulatory frameworks and strategic targets, while planning, design, and delivery decisions are largely controlled by market actors [72]. Under such conditions, progress depends not only on regulation itself but also on the ability of institutions to steer market behavior in a more coordinated way.

Public procurement plays a particularly important role in this context. Where the “most economically advantageous tender” continues to be interpreted mainly as the lowest price, sustainability goals remain difficult to operationalize [84]. In practice, such procurement logic can discourage innovation, reduce demand for low-carbon solutions, and reinforce conservative project choices [75].

This inertia is also visible in renovation practice. The implementation of more sustainable renovation approaches often requires coordination across design, construction, and supply-chain decisions rather than isolated technical upgrades. Recent studies on circular renovation and prefabricated renovation solutions show that low-carbon transition pathways depend on institutional readiness to support integrated and implementation-oriented approaches [85].

Although more sustainable procurement and renovation models are gradually emerging, their adoption remains uneven across the Baltic region. In Latvia, for example, environmental criteria are still not consistently embedded in procurement practice, even though some organizations have begun incorporating sustainability considerations into supplier selection [85]. This suggests that institutional change is taking place, but not yet at a scale sufficient to reshape mainstream construction practice.

Taking together, these conditions show that institutional inertia is not simply the absence of policy. It reflects the persistence of established procedures, narrow procurement logic, and limited coordination between public objectives and market implementation.

4.4. Cross-barriers

Sections 4.1–4.3 analysed digital, policy, and socio-cultural barriers separately. The thematic synthesis indicates that these barriers do not operate independently but form an interdependent socio-technical system. In the Baltic context, general WLC implementation challenges identified in the international literature are amplified by smaller-market conditions, including limited national datasets, evolving calculation methods, fragmented tools, uneven institutional readiness, and limited professional capacity. Table 5 therefore, links literature-based barriers with their Baltic contextualization and implementation implications.

Rather than functioning as isolated obstacles, these factors form a socio-technical system in which limitations in one domain can amplify constraints in the others.

While Table 5 summarizes the principal barriers and their implications, the relationships between digital, policy and socio-cultural domains are more complex and interconnected. Fig. 3 presents a conceptual synthesis of these interactions identified during thematic analysis.

Fig. 3 illustrates the interdependencies among the three groups of barriers identified through the thematic synthesis. Rather than acting independently, digital, policy, and socio-cultural barriers reinforce one another and collectively influence the implementation of Whole-Life Carbon assessment. For example, limited BIM-LCA interoperability and fragmented data infrastructures constrain compliance with emerging regulatory requirements, while inconsistent policy frameworks reduce incentives for investment in digital solutions and professional capacity building. Similarly, insufficient competencies and institutional inertia hinder the effective adoption of both technological innovations and regulatory measures. These interactions highlight the systemic nature of WLC implementation and explain why improvements in a single domain are unlikely to be effective without complementary progress in others.

The relationships shown in Fig. 3 emerged from recurring themes identified across multiple studies and were refined through axial coding during thematic synthesis.

Progress in WLC implementation therefore depends not only on improvements within individual domains but also on the alignment between digital infrastructures, policy instruments, and institutional capacities.

4.4.1. Interaction between digital systems and policy frameworks

The digital barriers discussed in Section 4.1, particularly limitations related to BIM and LCA interoperability, fragmented datasets, and low levels of automation, directly affect the implementation of the regulatory frameworks described in Section 4.2.

Table 5
Synthesis of literature-based WLC barriers, Baltic contextualization, and implementation implications.

Literature-based barrier	Baltic contextualization	Implementation implication
BIM–LCA interoperability and incomplete environmental data exchange	National WLC methods and approved tools are still evolving; BIM models are not consistently prepared for LCA use.	Mandatory WLC reporting may produce inconsistent results unless digital standards and modelling requirements are harmonized.
Limited availability and comparability of LCA/EPD data	Several Baltic assessments still depend on generic or foreign datasets; Estonia has advanced further through SARV/EHEA, while Latvia and Lithuania remain less developed.	Benchmarking and future carbon limit values may be delayed by insufficient representative national data.
Fragmented LCA tool landscape	Tools, datasets, and calculation assumptions differ across countries and projects.	Cross-country comparability and regulatory verification may be difficult without approved methodologies or quality assurance.
Uneven policy readiness	Estonia has developed national carbon assessment tools; Latvia and Lithuania rely more on voluntary or project-specific WLC practice.	EPBD-related WLC disclosure may be implemented at different speeds across the Baltic States.
Integration with EPC and national reporting systems	EPC systems and energy-performance classifications differ between Estonia, Latvia, and Lithuania.	WLC indicators will require technical and institutional adaptation of existing certification and registry systems.
Skills gaps and limited market readiness	WLC expertise remains uneven; cost-oriented procurement and limited demand reduce incentives for routine use.	WLC assessment may remain limited to pilot, public, or high-profile projects unless training and procurement criteria are strengthened.
Institutional inertia	Established procurement, design, and regulatory routines continue to prioritize conventional energy/cost criteria.	Policy ambition may not translate into practice without coordinated administrative guidance and market incentives.

The revised EPBD [12] requires mandatory calculation and disclosure of life-cycle global warming potential for new buildings. Although this requirement creates a regulatory driver for the adoption of WLC assessment, its effectiveness depends on the availability of digital workflows capable of producing reliable and reproducible results.

Currently, the alignment between regulatory requirements and digital infrastructures remains incomplete. Data exchange standards such as IFC were not originally designed to store environmental information required for life-cycle assessment. Consequently, important attributes, including Environmental Product Declaration data and life-cycle assumptions, may not be preserved during model exchange processes [37]. These limitations reduce the reliability of automated assessment workflows and often require additional manual interpretation.

Studies also show that identical building information models may produce different WLC results depending on the software environment, datasets, and mapping procedures used [8,27]. Such variability complicates the comparability of results and may introduce uncertainty in regulatory reporting.

In the Baltic context, where national WLC methodologies and approved calculation tools are still evolving, this mismatch between policy ambition and digital capability becomes particularly important. Regulatory harmonization without corresponding digital standardization may lead to inconsistent reporting outcomes, while digital tools without clear policy frameworks may fail to achieve widespread adoption. The primary constraint therefore emerges from the interaction

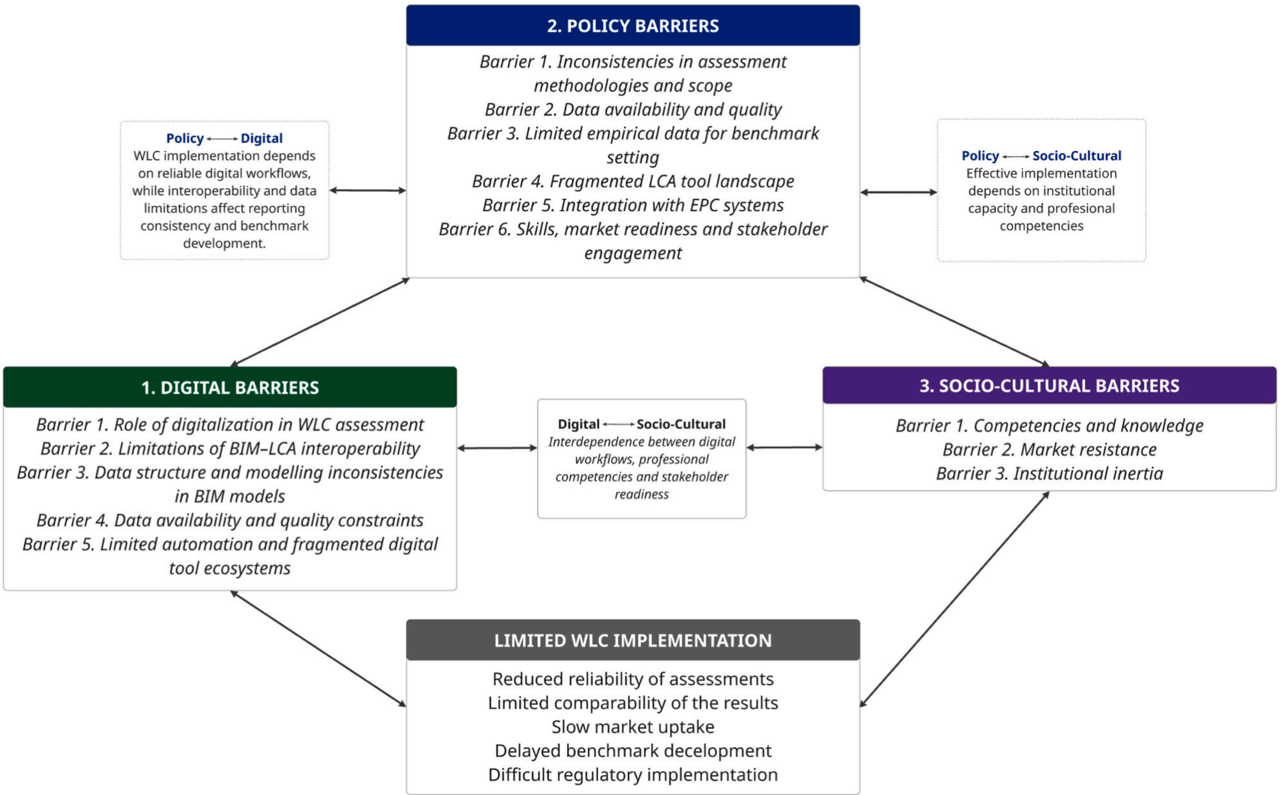

Fig. 3. Interactions and interdependencies among digital, policy and socio-cultural barriers affecting WLC implementation.

between these domains rather than from a single technological or regulatory limitation.

4.4.2. Interaction between policy frameworks and socio-cultural factors

The implementation of WLC policies also depends on institutional capacity and stakeholder readiness. As discussed in Section 4.2, the Baltic countries currently demonstrate different levels of preparedness for WLC integration. Estonia has introduced pilot carbon assessment tools and methodological frameworks, whereas Latvia and Lithuania still rely largely on voluntary or project-specific applications.

These differences affect the availability of empirical data needed for benchmark development. The regulatory framework established by the EPBD anticipates a gradual transition from disclosure-based reporting towards performance-based carbon limits. However, establishing such limits requires sufficiently large datasets describing the carbon performance of representative building types.

In smaller construction markets such as those in the Baltic region, the relatively limited number of WLC assessments slows the development of these datasets. This creates a structural gap between regulatory objectives and the evidence base required to support them.

Research on socio-technical transitions suggests that sustainable construction depends on the interaction between regulatory incentives, professional competencies, and perceptions of economic risk [16,72]. Evidence from the Baltic region also indicates that environmental awareness and sustainability priorities are strongly influenced by economic considerations and social perceptions [17].

When regulatory requirements increase technical complexity without parallel development of training programmes and institutional support mechanisms, implementation capacity may become a limiting factor. Under such circumstances, policies may formally exist but remain only partially integrated into everyday construction practice.

4.4.3. Interaction between digital technologies and socio-cultural factors

The digitalization of WLC assessment introduces additional organizational and cultural challenges. BIM-based LCA tools can support early design optimization and improve environmental decision-making. However, their effectiveness depends on consistent modelling practices and reliable quantity extraction [6,7].

In practice, BIM-based carbon assessment workflows are often perceived by practitioners as technically complex and time-intensive [8]. Preparing models suitable for LC assessment frequently requires additional modelling effort, dataset selection, and interpretation of results.

In construction environments where project decisions are strongly influenced by short-term financial considerations, this additional effort may be perceived as a cost rather than a benefit. Consequently, digital carbon assessment tools may remain underutilized even when technological solutions are available.

Procurement structures further reinforce this dynamic. Public procurement systems in many Baltic construction markets continue to prioritize lowest-cost evaluation criteria. Under these conditions, contractors and developers have limited incentives to invest in advanced modelling practices or life-cycle optimization strategies.

Technological capability alone is therefore insufficient to transform construction practices. The adoption of digital WLC assessment tools depends on institutional incentives, professional competencies, and market demand.

4.4.4. Critical transition bottlenecks

The synthesis of digital, policy, and socio-cultural barriers highlights several structural constraints affecting WLC implementation in the Baltic construction sector.

One constraint relates to the relationship between regulatory requirements and digital infrastructure. Mandatory WLC reporting presupposes interoperable modelling environments and consistent environmental datasets. Without harmonized digital standards, assessment results may vary between projects, reducing comparability and weakening confidence in reported carbon performance.

Another challenge concerns the limited availability of empirical datasets required for benchmark development. Establishing carbon performance thresholds requires statistically robust evidence describing the environmental performance of representative building typologies. In the Baltic construction markets, the relatively small number of WLC assessments slows the generation of such datasets and delays the transition from disclosure-based reporting towards performance-based regulation.

Institutional capacity represents an additional constraint. Expanding regulatory requirements increase the demand for specialized expertise in LCA, digital modelling, and environmental data management. However, professional competencies in these areas remain unevenly distributed across the sector. Without targeted training programmes and technical guidance, WLC assessment may remain confined to specialized projects rather than becoming a routine component of design practice.

Market structures also influence the pace of transition. Procurement systems that prioritize lowest initial cost reduce incentives for innovation and discourage the adoption of low-carbon materials or design strategies. Such procurement logic reinforces conservative investment behavior and slows the diffusion of sustainability practices across the construction sector.

Taken together, these structural constraints indicate that WLC implementation cannot be achieved through technological innovation or regulatory change alone. Effective transition requires coordinated development across digital infrastructures, regulatory frameworks, professional competencies, and market incentives.

4.5. Prioritization of barriers

The analysis indicates that not all barriers have equal influence on WLC implementation. Three categories of impact can be identified:

- System-critical barriers include interoperability limitations, lack of standardized datasets, and absence of harmonized methodologies. These barriers directly affect the feasibility of WLC assessment and its integration into regulatory frameworks.
- Enabling barriers relate to professional competencies, data availability, and tool accessibility. While not preventing implementation entirely, they significantly influence the quality and scalability of assessment processes.
- Contextual barriers include market preferences, procurement practices, and stakeholder awareness. These factors shape the speed and extent of adoption but are dependent on regulatory and technological conditions.

This prioritization highlights that addressing digital and methodological standardization is a prerequisite for broader socio-cultural and market transformation.

Overall, the findings suggest that WLC implementation in the Baltic construction sector should be understood as a socio-technical system in transition, where digital tools, regulatory frameworks, and stakeholder behavior co-evolve. Within such systems, barriers are not independent constraints but interconnected elements that shape the pace and direction of transformation. Consequently, effective implementation depends on alignment across these domains rather than progress within a single dimension.

5. Discussion and research gaps

The findings of this study indicate that barriers to WLC implementation in the Baltic construction sector are not isolated constraints but interdependent elements of a broader socio-technical system. While previous research has frequently examined technological, regulatory, or economic challenges separately, the results of this review demonstrate that the most significant limitations arise from the interaction between these domains.

In particular, the analysis highlights that digital limitations, regulatory frameworks, and socio-cultural factors mutually reinforce each other, shaping both the feasibility and the pace of WLC adoption. This shifts the interpretation of WLC implementation from a technical problem towards a systemic transition challenge.

The contribution of this study lies in providing an integrative perspective on WLC implementation barriers by combining digital, policy, and socio-cultural dimensions within a single analytical framework. While earlier studies have identified individual barriers, this research advances the field by explicitly examining their interactions and systemic implications within a regional context. In doing so, it contributes to a more comprehensive understanding of how WLC assessment can be operationalized in smaller construction markets, where institutional capacity, data availability, and digital maturity remain uneven.

Digitalization is frequently presented as a key enabler of WLC implementation, particularly through the integration of building information modelling and life-cycle assessment tools. However, the findings of this review suggest that technological capabilities alone are insufficient to support large-scale adoption. Limitations related to data interoperability, fragmented digital tool ecosystems, and inconsistencies in modelling practices continue to affect the reliability and comparability of WLC calculations [6–8].

At the same time, the regulatory landscape in Europe is evolving rapidly. The revised Energy Performance of Buildings Directive introduces mandatory life-cycle carbon disclosure for new buildings and requires Member States to develop national frameworks for carbon reporting. While these developments create an important policy driver, their implementation depends on the availability of digital infrastructures and institutional capacities capable of supporting consistent WLC assessment.

A key insight emerging from this study is the structural mismatch between regulatory ambition and digital capability. The revised EPBD introduces mandatory WLC reporting requirements, yet the digital infrastructure required to support consistent and reproducible assessments remain underdeveloped. This creates a situation where policy frameworks depend on technical systems that are not yet fully mature, leading to inconsistencies in implementation and uncertainty in reported results.

The Baltic case clarifies which WLC implementation barriers are region-specific and which have broader relevance for smaller construction markets. Region-specific challenges include uneven national WLC readiness, limited country-specific carbon datasets, few completed WLC assessments for benchmark development, and differences between Estonia, Latvia, and Lithuania in calculation tools, energy-performance classifications, and policy implementation pathways. However, several barriers are not unique to the Baltic region, including BIM–LCA interoperability problems, dependence on generic or foreign EPD datasets, fragmented LCA tool ecosystems, limited professional capacity, and cost-oriented procurement. The broader relevance of the Baltic case, therefore, lies in showing how EU-level WLC requirements may be difficult to operationalize in smaller markets when regulatory ambition develops faster than data infrastructure, digital standardization, administrative procedures, and sectoral competencies.

Another important finding of this review concerns the role of socio-cultural factors in shaping the adoption of WLC practices. Market behaviors in the construction sector remain strongly influenced by short-term economic considerations, and procurement systems frequently prioritize lowest-cost solutions. Under these conditions, life-cycle optimization strategies and low-carbon material choices may receive limited attention despite their long-term environmental benefits.

Professional competencies and institutional capacity also play an important role. The adoption of life-cycle carbon assessment requires specialized expertise in digital modelling, environmental data management, and sustainability evaluation. However, the availability of such expertise remains uneven across the construction sector. Without targeted training programmes and stronger collaboration between academia, industry, and public authorities, the implementation of WLC assessment may remain limited to specialized projects.

These findings indicate that WLC implementation should be understood as a socio-technical transition rather than a purely technological or regulatory challenge. Digital tools, policy frameworks, and stakeholder behavior are closely interconnected, and progress in one domain depends on developments in the others.

The synthesis of the reviewed literature also highlights several areas where further research is needed. One important limitation concerns the lack of empirical data describing WLC readiness in Baltic construction markets. Existing studies largely focus on technical methodologies or policy frameworks, while fewer studies investigate how construction professionals, developers, and public institutions perceive and implement life-cycle carbon assessment in practice.

Another research gap relates to the availability of harmonized environmental datasets. Reliable benchmarking of life-cycle carbon performance requires comprehensive and comparable material databases. In many Baltic construction markets, such datasets remain incomplete or fragmented, which complicates the development of regional benchmarks and carbon performance thresholds.

A further area requiring investigation concerns the integration of digital modelling environments with regulatory reporting systems. The introduction of WLC indicators into Energy Performance Certificates creates new requirements for interoperability between building information models, life-cycle assessment tools, and national building registries. Research addressing these integration challenges remains limited.

Finally, additional research is needed to examine the influence of procurement practices and investment behavior on the adoption of low-carbon construction strategies. Understanding how financial incentives, regulatory frameworks, and market expectations interact may provide important insights into how WLC assessment can be more effectively embedded within construction decision-making processes.

Overall, the results of this review indicate that achieving meaningful reductions in life-cycle carbon emissions requires a coordinated socio-technical transition, where digital infrastructures, regulatory frameworks, and institutional capacities are aligned. Rather than focusing on isolated improvements in tools or policies, future research should prioritize understanding how these elements can be integrated into coherent implementation pathways that effectively support WLC adoption.

6. Conclusions

This study examined the technological, policy, and socio-cultural barriers affecting the implementation of Whole-Life Carbon assessment in the Baltic construction sector. Through a systematic review and thematic synthesis of the literature, the analysis revealed that the transition towards WLC-based decision-making is shaped not by a single limiting factor but by the interaction of several interdependent systems.

The results indicate that digitalization plays a crucial role in enabling WLC assessment, particularly through the integration of building information modelling and life-cycle assessment tools. However, current digital infrastructures remain constrained by interoperability limitations, fragmented datasets, and inconsistent modelling practices. These challenges reduce the reliability and comparability of WLC calculations and limit the scalability of digital workflows across projects and regulatory contexts.

At the regulatory level, the evolving European policy framework introduces strong drivers for WLC implementation. The revised Energy Performance of Buildings Directive establishes mandatory life-cycle carbon reporting requirements and encourages the development of national frameworks for carbon assessment. Nevertheless, the readiness of national construction sectors to implement these requirements varies. Within the Baltic region, Estonia has made notable progress in developing methodological tools and pilot initiatives, while Latvia and Lithuania continue to rely mainly on voluntary or project-based applications.

The analysis also highlights the importance of socio-cultural and institutional factors in shaping the adoption of WLC practices. Market behavior in the construction sector remains strongly influenced by short-term economic considerations, and procurement systems frequently prioritize lowest-cost solutions. At the same time, the availability of professional competencies related to life-cycle assessment and digital modelling remains uneven across the sector. These conditions may limit the practical integration of WLC assessment into routine design and construction processes.

The findings suggest that the implementation of WLC assessment in the Baltic construction sector is constrained by a set of interdependent barriers rather than isolated challenges. The most critical limitations arise from the interaction between digital infrastructures and regulatory requirements, particularly where policy ambitions exceed current technological capabilities.

From a policy perspective, the results highlight the need for coordinated development of national methodologies, environmental datasets, and digital infrastructures aligned with EN 15978 and Level(s) frameworks. From an industry perspective, strengthening professional competencies and integrating WLC criteria into procurement processes are essential for enabling practical implementation.

Rather than focusing on individual solutions, effective WLC implementation requires a systemic approach that aligns technological, institutional, and market conditions.

The results of this review also highlight several priorities for future research and policy development. Strengthening national environmental datasets, improving interoperability between digital modelling and assessment tools, and expanding professional training related to life-cycle carbon analysis are essential steps for enabling more consistent implementation of WLC assessment. In addition, greater attention should be given to the role of procurement systems and financial incentives in shaping construction-sector behavior.

Overall, the transition towards life-cycle carbon-based decision-making represents an important opportunity to support climate-neutral construction in Europe. For the Baltic construction sector, achieving this transition will require coordinated efforts from policymakers, industry stakeholders, and research institutions to ensure that technological innovation, regulatory frameworks, and institutional capacities develop in parallel.

7. Limitations

Despite the insights provided by this review, several limitations should be acknowledged. The analysis focused primarily on literature addressing the Baltic construction sector and therefore reflects the specific regulatory, institutional, and market conditions of this region. While many of the identified barriers may also be relevant to other European construction markets, the findings should be interpreted with consideration of the regional context.

The review was based on peer-reviewed publications and selected policy and institutional reports identified through the systematic search process. Although this approach ensures methodological transparency, it may not capture all ongoing industry practices or unpublished professional knowledge related to Whole-Life Carbon assessment.

In addition, the study relied on qualitative thematic synthesis rather than quantitative meta-analysis. As a result, the conclusions emphasize conceptual relationships between digital, policy, and socio-cultural barriers rather than providing statistical estimates of their relative importance. Future empirical research based on surveys, case studies, and project-level datasets could provide further insights into how these barriers influence WLC implementation in practice.

Use of artificial intelligence tools

During the preparation of this article, AI tools were used for language refinement only. All content was critically reviewed by the authors.

CRediT authorship contribution statement

Eglė Klumbytė: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Iryna Osadcha:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Paulius Vestfal:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Liga Puzule:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Anatolijs Borodinecs:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Lina Šeduikytė:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Data availability

No data was used for the research described in the article.

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