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Evaluating sustainable building assessment systems: a comparative analysis of GBRS and WBLCA

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This comprehensive review examines sustainable building assessment systems, focusing on Green Building Rating Systems (GBRS) like BREEAM and Whole Building Life Cycle Assessment (WBLCA) approaches in the context of achieving the United Kingdom's climate targets. The study highlights significant limitations in GBRS, particularly their inadequate focus on embodied carbon emissions and alignment with national climate goals. WBLCA emerges as a promising solution, offering a holistic methodology for quantifying environmental impacts across a building's entire lifecycle. The research explores the integration of advanced techniques such as Building Information Modelling (BIM), automated data collection, and artificial intelligence to enhance WBLCA's effectiveness. While WBLCA shows potential in driving the built environment sector towards climate targets, the study identifies challenges including methodological issues, data quality, and the need for standardisation. This article emphasises the importance of aligning building assessment systems with national climate targets and carbon budgets. It concludes by calling for a paradigm shift from static, point-based rating systems to dynamic, quantitative approaches in sustainable building assessment, highlighting the need for interdisciplinary collaboration and education to support this transition.

KEYWORDS

green building rating systems (GBRS), whole building life cycle assessment (WBLCA), embodied carbon emissions, climate targets, building information modelling

1 Introduction

As concerns around the climate crisis intensify, the construction industry faces increasing pressure to minimise its carbon emissions. Buildings contribute around 40% of global energy use and a substantial portion of greenhouse gas emissions, making them a critical focus area for sustainability efforts (United Nations Environment Programme, 2022; Intergovernmental Panel on Climate Change IPCC, 2023). Sustainability in buildings involves balancing environmental, social, and economic goals to create structures that minimise resource use, reduce emissions, and enhance occupant wellbeing while remaining economically viable over their lifecycle (UN, 1987). The building sector's role in reaching the United Kingdom's net-zero emissions target by 2050 is especially significant, given that operational improvements in new and existing buildings can only address part of the sector's environmental impact.

This review specifically examines sustainable building assessment systems within the United Kingdom context, a focus chosen for several compelling reasons. The United Kingdom serves as an ideal case study due to its distinctive regulatory environment, established through the Climate Change Act, which sets legally binding carbon budgets and emissions reduction targets. This legislative framework creates clear benchmarks against which to evaluate the effectiveness of different assessment approaches. The United Kingdom's position as a pioneer in sustainable building assessment further justifies this geographical focus. The development of BREEAM in 1990 established the United Kingdom as an early leader in standardized environmental assessment methods for buildings. This historical context provides valuable insights into the evolution of assessment systems and their adaptation to changing environmental priorities over time.

Additionally, the United Kingdom construction sector possesses unique characteristics that influence the implementation of assessment methods. These include its specific building stock composition, with a high proportion of existing buildings requiring retrofit, its established professional institutions and industry bodies, and its planning and building regulation systems. These factors create a distinct environment for studying the practical application and effectiveness of different assessment approaches. The United Kingdom's commitment to achieving net-zero emissions by 2050 also makes it particularly relevant for examining how assessment systems can support climate targets. This ambitious goal requires significant transformation in building design, construction, and operation practices, making the evaluation of assessment methods especially pertinent. While this United Kingdom focus provides a specific lens for analysis, the findings have broader implications for other jurisdictions pursuing similar environmental objectives. The challenges and opportunities identified through studying the United Kingdom context can inform the development and implementation of assessment systems in other countries, particularly those with similar regulatory frameworks or climate commitments.

As buildings become more energy-efficient in their operational phase, embodied carbon—the carbon emitted during the production, transport, and construction of building materials (i.e., excluding that emitted during use and end-of-life phases)—represents a growing share of total building emissions. According to the U.S. Energy Information Administration (EIA), energy intensity (energy use per square foot) in the U.S. commercial building sector decreased by 12% between 2005 and 2020, despite a 14% increase in total floor space over the same period (U.S. Energy Information Administration, 2021). The International Energy Agency (IEA) reports that global energy efficiency improvements in buildings have averaged 1.5% annually since 2015, with significant contributions from better insulation, energy-efficient appliances, and lighting systems (Energy Agency I, 2021). In the European Union, energy consumption in buildings has decreased by **8%** since 2005, despite a **10%** increase in floor area, largely due to the Energy Performance of Buildings Directive (EPBD) and the adoption of nearly zero-energy buildings (nZEB) (Energy Agency I, 2021) (European Commission, 2021). Assessing and reducing both operational and embodied carbon is essential for meeting the United Kingdom's long-term climate goals (HM Government, 2021).

Prior to 1990, environmental assessment of buildings in the United Kingdom was primarily governed by Building Regulations, focusing on basic safety and performance standards. The Building Regulations 1985 established minimum requirements for energy efficiency through Part L, though these were limited to prescriptive standards for building fabric and services (Howard, 1990). The Building Research Establishment (BRE) introduced BREEAM in 1990 as the first comprehensive environmental assessment method for buildings. This introduction predated major climate policy developments, indicating its origin was driven by industry recognition of environmental impacts rather than climate policy compliance (Yates et al., 1998). The initial BREEAM methodology focused on operational energy efficiency, water consumption, and indoor environmental quality (Prior, 1993). The period between 1995–2005 saw significant developments in building regulations, particularly through the 2002 revision of Part L, which introduced more stringent energy efficiency requirements (Office of the Deputy Prime Minister ODPM, 2002). During this period, BREEAM expanded its scope to include different building types and introduced its now-familiar rating system of Pass to Excellent (Hassler and Kohler, 2014). The implementation of the Kyoto Protocol in 2005 marked a turning point in climate policy. The subsequent 2006 Building Regulations amendments introduced significant changes to energy efficiency requirements (Department for Communities and Local Government DCLG, 2006). BREEAM responded by revising its energy performance weightings and introducing more detailed assessment criteria for CO2 emissions (Grace, 2000). The Climate Change Act 2008 established legally binding carbon reduction targets, leading to further revisions of both regulatory requirements and voluntary standards. Building Regulations 2010 and 2013 introduced progressively stricter energy performance requirements (HM Government, 2010). BREEAM's 2011 and 2014 updates reflected these changes while maintaining its position ahead of regulatory minimums in areas such as material sustainability and waste management (BREEAM, 2024).

The relationship between BREEAM and Building Regulations has been complementary rather than directly causal. While BREEAM has often set higher standards than regulatory minimums, the adoption of similar approaches in subsequent Building Regulations revisions suggests indirect influence through market transformation (Schweber and Haroglu, 2014).

Green Building Rating Systems (GBRS), such as BREEAM and LEED, dominate the field of building sustainability assessment, with methodologies like Life Cycle Assessment (LCA) and standards such as Passivhaus (and similar energy-efficient frameworks) following behind. While GBRS are widely recognized and adopted by the construction industry, they face limitations in addressing comprehensive sustainability goals, particularly in evaluating embodied carbon and lifecycle impacts (Hollberg et al., 2020).

Lifecycle impacts in the context of Building LCA refer to the environmental effects associated with all stages of a building's life cycle, from raw material extraction and manufacturing to construction, operation, maintenance, and end-of-life disposal or recycling, assessed to understand and mitigate the building's overall sustainability footprint (ISO 14040, 2006).

WBLCA, in comparison to GBRS, offers a more detailed and quantitative approach, assessing the environmental impacts of a building across its entire life cycle, from material extraction to demolition (Buyle et al., 2013). This work aims to evaluate the effectiveness of GBRS and WBLCA in contributing to sustainable building practices and to identify which system better aligns with the United Kingdom's climate goals.

Sustainable building practices focus on reducing the environmental, social, and economic impacts of buildings throughout their lifecycle, emphasizing energy efficiency, resource conservation, waste reduction, and occupant wellbeing (Building Research Establishment, 2024).

Aligning with United Kingdom climate goals involves meeting specific national targets, such as achieving net-zero carbon emissions by 2050, as mandated by the United Kingdom Climate Change Act (2008 Amendment). In the context of Building LCA, this requires quantifying and reducing embodied and operational carbon emissions, adhering to policies like the Future Homes Standard (2025), and ensuring buildings contribute to the United Kingdom's broader decarbonization agenda (HM Government, 2021).

1.1 Sustainable building assessment systems

Green Building Rating Systems are frameworks developed to assess, score, and certify the environmental performance of buildings. Popular systems like BREEAM (Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design), and Green Star evaluate buildings based on various sustainability criteria, such as energy use, water conservation, indoor environmental quality, and materials. By assigning scores across these criteria, GBRS encourage developers and architects to integrate environmentally responsible practices into building projects. Certified buildings receive a rating or certification level—such as Platinum, Gold, or Silver for LEED, and Outstanding, Excellent, or Very Good for BREEAM—based on their performance.

Although GBRS have helped raise awareness and drive improvement in operational efficiency, they have several key limitations including a limited scope of LCA, lack of regional adaptation, focus on certification over performance and limited incentives for innovation. One of the most notable is their limited consideration of embodied carbon.

Many GBRS focus primarily on operational energy efficiency and do not fully integrate a comprehensive life cycle assessment (LCA) approach, which includes embodied carbon, material extraction, construction, and end-of-life impacts (Pomponi and Moncaster, 2016). GBRS often use generic criteria that may not account for regional variations in climate, resources, and cultural practices, leading to less effective or contextually inappropriate solutions (Berardi, 2013). GBRS often emphasize achieving certification rather than ensuring long-term building performance, leading to a "tick-box" mentality where buildings may not perform as intended post-certification (Newsham et al., 2009). The certification process can be expensive and time-consuming, which may discourage smaller projects or developers with limited budgets from pursuing certification (Doan et al., 2017; Sharifi and Murayama, 2013) Most GBRS provide a one-time certification without requiring ongoing performance monitoring, which can lead to a gap between designed and actual building performance (Scofield, 2013). GBRS often reward compliance with predefined criteria rather than encouraging innovative solutions that go beyond the standards (Cole, 2005).

Since GBRS tend to prioritize criteria related to energy efficiency during the operational phase, they often overlook the significant emissions associated with materials and construction processes. Furthermore, GBRS typically provide a one-time certification based on a building's design and construction, with little to no follow-up during its operational phase. As a result, the system does not account for changes in building performance over time, limiting its ability to ensure long-term sustainability.

Whole Building Life Cycle Assessment (WBLCA) is a more comprehensive framework designed to evaluate a building's environmental impact across its entire life cycle. Unlike GBRS, which largely focus on operational efficiency, WBLCA considers all stages of a building's lifecycle, including raw material extraction, manufacturing, transportation, construction, operational use, and end-of-life processes. By using this "cradle-to-grave" approach, WBLCA can provide a detailed understanding of a building's total carbon footprint.

WBLCA is grounded in international standards such as EN 15978 and EN 15804, which establish guidelines for evaluating environmental performance in construction and generating Environmental Product Declarations (EPDs) for building materials. These standards ensure that WBLCA provides consistent, comparable results, enabling stakeholders to make informed decisions about building materials, design strategies, and construction practices that align with national and global climate goals (Anand and Amor, 2017). Given its focus on both embodied and operational carbon, WBLCA is increasingly seen as a valuable tool for setting and achieving project-level carbon budgets that support the United Kingdom's climate targets.

1.2 Advanced tools to support WBLCA

The successful implementation of WBLCA depends on reliable, high-quality data, which can be difficult to obtain for all phases of a building's life cycle. Traditional WBLCA assessments often require extensive manual data collection, making them time-consuming and resource-intensive (Cabeza et al., 2014).

While Building Information Modelling (BIM) has been a well-established technology in the construction industry for over a decade, its integration with Whole Building Life Cycle Assessment (WBLCA) represents a significant advancement in addressing data availability and complexity challenges.

Recent advancements in automated data collection and machine learning (ML) offer promising solutions to streamline WBLCA and improve its accuracy. For example, IoT-enabled sensor networks have been successfully deployed in building projects to provide real-time monitoring of energy use, material performance, and environmental conditions. Studies such as those by Shadram et al. and Cavalliere et al. demonstrate how

IoT devices can enhance data accuracy by reflecting actual building performance rather than relying on static assumptions (Shadram et al., 2016; Cavalliere et al., 2019). Similarly, machine learning algorithms have been applied to analyse large datasets collected through these methods, helping identify trends and provide predictive insights that support proactive decision-making. For instance, Robati et al. and Santos et al. have shown how ML models can predict the environmental performance of different materials and design choices, enabling stakeholders to make informed decisions at every stage of a project (Robati et al., 2016; Santos et al., 2019).

These technologies, when integrated with Building Information Modelling (BIM), create a powerful synergy for sustainable building assessment. For example, the work of Soust-Verdaguer et al. highlights how BIM-integrated WBLCA, combined with IoT and ML, can reduce embodied carbon emissions and improve lifecycle performance. Such integrations have been successfully implemented in projects like the One Angel Square building in Manchester, United Kingdom, where IoT and ML were used to optimize energy efficiency and reduce operational carbon emissions (Soust-Verdaguer et al., 2017; Shadram et al., 2016).

Building Information Modelling (BIM), particularly at Level 2 (the minimum standard for collaborative BIM in the United Kingdom), offers a comprehensive and structured digital representation of a building, containing detailed information about its components, materials, quantities, and specifications. At this level, BIM enables the integration of data from multiple stakeholders into a shared digital environment, facilitating seamless collaboration and data exchange. By leveraging this data-rich resource, BIM-integrated WBLCA can streamline the data collection process, reducing the time and effort required for manual data entry (UK BIM Framework, 2024).

The parametric nature of BIM Level 2 models enables automated data extraction and updates, facilitating the integration of WBLCA assessments throughout the building's life cycle. This seamless data flow overcomes the limitations of conventional LCA approaches, which often rely on fragmented and incomplete data sources, leading to inconsistencies and inaccuracies. Furthermore, the structured data environment of BIM Level 2 supports the accurate quantification of embodied carbon emissions, addressing a critical gap in traditional Green Building Rating Systems (GBRS).

BIM implementation is categorized into different levels of maturity, ranging from Level 0 (non-collaborative, 2D CAD-based drafting) to Level 3 (fully integrated, cloud-based collaboration). Level 2, which is the focus of this discussion, represents a collaborative approach where all stakeholders use their own 3D CAD models, but information is shared through a common file format (e.g., IFC) and managed within a shared data environment. This level of BIM is widely adopted in the United Kingdom and aligns with the requirements of sustainable building assessment systems like WBLCA (BSI Standards, 2013).

Building Information Modelling (BIM), particularly at Level 2 and above, enables project teams to automate data collection for the life cycle inventory (LCI) by integrating with external databases or digital tools. For example, BIM models can be linked to Environmental Product Declaration (EPD) databases or life cycle assessment (LCA) software, which are updated with real-time data on material properties, energy use, and environmental impacts. This integration allows for the automatic extraction of relevant data from the BIM model, such as material quantities, specifications, and construction processes, and feeds it directly into the LCI (Soust-Verdaguer et al., 2017; Cavalliere et al., 2019; Shadram et al., 2016).

Additionally, BIM's parametric capabilities enable real-time updates to the LCI as the building design evolves. For instance, if a material or component is changed in the BIM model, the associated environmental data can be automatically updated in the LCI, ensuring that the assessment remains accurate and up to date throughout the design and construction phases. This dynamic linkage between BIM and LCI databases reduces the need for manual data entry, minimizes errors, and enhances the overall efficiency of the WBLCA process.

By integrating Building Information Modelling (BIM) with Whole Building Life Cycle Assessment (WBLCA), project teams can make data-driven adjustments that optimize a building's environmental performance, particularly in terms of carbon emissions (both embodied and operational). While embodied carbon—associated with material extraction, manufacturing, and construction—is largely locked in once the building is completed, BIM-integrated WBLCA allows for real-time adjustments during the design and construction phases. For example, if the BIM model identifies high embodied carbon materials, the design team can substitute them with lower-carbon alternatives before construction begins (Pomponi and Moncaster, 2016; Cavalliere et al., 2019).

For operational carbon—emissions resulting from energy use during the building's lifecycle—BIM-integrated WBLCA enables continuous monitoring and optimization. IoT-enabled sensor networks can provide real-time data on energy consumption, occupancy patterns, and environmental conditions, allowing building operators to adjust systems (e.g., HVAC, lighting) to minimise operational carbon emissions (Shadram et al., 2016).

While Whole Building Life Cycle Assessment (WBLCA) provides a more comprehensive framework for evaluating a building's environmental impact, its ability to reflect actual performance depends on the quality and granularity of the data used. In its conventional form, WBLCA often relies on static assumptions about energy use, material performance, and grid energy mix, which may not capture real-time variations. For example, operational energy use is typically modelled based on historical or projected data, rather than real-time monitoring of energy consumption and grid carbon intensity (Shadram et al., 2016).

However, when integrated with real-time data sources, such as IoT-enabled sensor networks and grid energy mix data, WBLCA can provide a more accurate reflection of actual performance. This dynamic approach allows WBLCA to better approximate the building's actual carbon footprint during operation.

That said, even with real-time data integration, WBLCA still involves some level of approximation, particularly for embodied carbon, which is based on material production and supply chain data that may not be fully transparent or up to date. Therefore, while WBLCA represents a significant improvement over traditional assessment methods, it should be viewed as a dynamic tool for continuous improvement rather than a definitive measure of actual performance.

1.3 Gaps and goals

Current research in building environmental assessment reveals several critical gaps that this study aims to address. First, while both GBRS and WBLCA have been studied individually, there is limited systematic analysis comparing their effectiveness in supporting national climate targets. This gap is particularly significant for the United Kingdom construction sector, where the Climate Change Act establishes legally binding carbon budgets that require precise quantification and management of environmental impacts.

Existing literature lacks comprehensive evaluation of how these assessment methods adapt to evolving environmental priorities, especially regarding embodied carbon measurement. As buildings become more energy-efficient in operation, the relative importance of embodied carbon increases, yet current research provides insufficient guidance on how assessment methods can effectively capture and evaluate these impacts throughout the building lifecycle.

The rapid advancement of technology presents another significant research gap. While digital technologies like Building Information Modelling and automated data collection systems offer potential solutions for improving assessment accuracy and efficiency, research has not adequately examined how these technologies can be integrated with existing assessment frameworks to enhance their effectiveness. The potential for these technologies to address current limitations in building assessment methods remains largely unexplored.

Additionally, there is insufficient understanding of how assessment methods can better align with and support the achievement of specific national climate commitments, particularly in the context of the United Kingdom's ambitious carbon reduction targets. The relationship between assessment methodologies and policy frameworks requires further investigation to ensure that assessment systems effectively support the achievement of climate goals.

These research gaps become increasingly significant as the construction industry seeks more effective approaches to environmental assessment and performance improvement. The lack of comparative analysis between assessment methods limits our understanding of their relative strengths and weaknesses in supporting climate goals. This study addresses these gaps through systematic analysis of both traditional and emerging assessment approaches.

This research aims to address these gaps through several interconnected objectives. The study examines the effectiveness of GBRS and WBLCA in promoting sustainable building practices and supporting climate goals through comparative analysis of their assessment criteria, scope, and alignment with climate targets. It analyses the limitations of GBRS in addressing environmental impacts, particularly concerning embodied carbon and lifecycle performance, while exploring WBLCA's potential as a comprehensive, data-driven tool for achieving sustainability goals. Additionally, the research examines the role of advanced techniques such as BIM, automated data collection, and machine learning in improving assessment accuracy and efficiency.

WBLCA primarily focuses on quantifying carbon emissions (both embodied and operational) and other environmental impacts such as energy use, water consumption, and material resource depletion. However, it does not yet fully capture all aspects of environmental impact, such as embodied biodiversity or social sustainability, for which data is either emerging or not yet widely available. WBLCA aligns with climate targets (e.g., reducing carbon emissions) but it does not directly address broader sustainability goals such as the UN Sustainable Development Goals (SDGs), which encompass social, economic, and environmental dimensions. That said, WBLCA represents a significant step forward in addressing the embodied carbon gap left by GBRS like BREEAM, which primarily focus on operational energy efficiency. By providing a cradle-to-grave assessment of a building's carbon footprint, WBLCA enables stakeholders to make more informed decisions about material selection, design strategies, and construction practices that align with national and global climate goals.

Through this analysis, the study seeks to contribute to the development of more effective building assessment approaches that can better support the achievement of climate targets. The findings aim to inform policy development, industry practice, and future research directions in sustainable building assessment, particularly within the United Kingdom context but with potential implications for other jurisdictions pursuing similar environmental objectives.

2 Sustainable building assessment systems

2.1 Need for sustainable building assessment systems

GBRS, such as LEED, BREEAM, Green Star, DGNB (German Sustainable Building Council), CASBEE (Comprehensive Assessment System for Built Environment Efficiency), and Green Globes, are voluntary, market-driven standards that assess the sustainability of buildings through multi-criteria evaluation (Doan et al., 2017; Illankoon et al., 2017). These systems cover various aspects, including energy use, water consumption, material impacts, waste management, and indoor environmental quality (Balaban and Puppim de Oliveira, 2014).

The origin and need for GBRS arose from growing concerns about the significant environmental footprint of buildings and the lack of standardized methods to evaluate environmental performance (Berardi, 2013). With no established frameworks to quantify impacts and drive sustainable practices in design, construction, and operation, GBRS aimed to provide a comprehensive assessment of a building's sustainability by evaluating multiple criteria and awarding certification levels based on the achieved performance (e.g., Platinum, Gold, Silver) (Doan et al., 2017; Illankoon et al., 2017).

2.1.1 BREEAM (building research establishment assessment method)

The key objectives behind developing BREEAM were to enhance buildings' operational performance and minimize environmental impacts, provide a standardized method to measure and evaluate buildings' environmental effects, and objectively assess and rate the sustainability of building developments (In Use Team B, 2020). BREEAM aimed to drive sustainable construction practices by setting benchmarks and providing third-party certification of a building's environmental performance across various criteria.

TABLE 1 Changes in BREEAM assessment categories and weightings over time.

Category	1990s–2000s	2010s	2020s
Energy	25%–30%	25%	25%
Health and Well-being	5%–10%	15%	15%
Materials	10%–15%	15%	15% (incl. EPDs)
Water	5%–10%	8%	8%
Land Use and Ecology	5%	7%	7% (incl. biodiversity)
Pollution	5%	5%	5% (incl. resilience)
Innovation	N/A	10%	10%

BREEAM's structure is composed of assessment categories, with credits associated with a subset of weighted criteria, resulting in a total score that translates into a rating dependent on the range of the score (In Use Team B, 2020). The assessment categories cover energy, water, materials, waste, pollution, health and wellbeing, management, land use and ecology, and transport (In Use Team B, 2020). Each category consists of a set of criteria, with credits awarded for meeting specific targets, and the credits are weighted to reflect their relative importance in terms of environmental impact (In Use Team B, 2020).

As shown in Table 1, the system allocates different weightings to reflect the relative importance of various environmental aspects. Energy efficiency receives the highest weighting at 25%, followed by materials and health and wellbeing at 15% each, reflecting the prioritization of operational performance and occupant wellbeing.

Based on the total score achieved, buildings are awarded ratings ranging from Pass to Outstanding, providing a clear indication of their overall sustainability performance (In Use Team B, 2020). The different BREEAM certification levels are as follows:

- Outstanding (≥85%): Representing pioneering best practice and exemplary sustainability performance, with minimal negative environmental impact and high standards across all assessment categories.
- Excellent (≥70%): Demonstrating high sustainability performance beyond standard practice, with significant achievements in energy and water efficiency, responsible sourcing of materials, minimized pollution levels, and implementation of best practices in sustainable design.
- Very Good (≥55%): Indicating that the building has achieved high standards of sustainability, exceeding regulatory requirements and incorporating a range of sustainable design features and practices.
- Good (≥45%): Buildings have incorporated sustainable design features and practices that provide good environmental performance and align with standard industry practice.
- Pass (≥30%): Representing the minimum level of sustainability performance required for BREEAM certification, with buildings meeting the basic requirements but possibly having limited sustainable design features or practices.
- Unclassified (<30%): Buildings that fail to achieve the minimum 30% score and do not qualify for BREEAM certification.

2.1.2 Life cycle assessment (LCA) standards

Complementing GBRS, Life Cycle Assessment standards such as EN 15978 and EN 15804 provide robust, internationally recognized methodologies for quantifying environmental impacts across a building's full life cycle, including emissions, resource use, and toxicity.

While Life Cycle Assessment (LCA) is widely regarded as a robust methodology for evaluating environmental impacts, it is important to acknowledge that its robustness depends heavily on the quality, completeness, and transparency of the data used. LCA is inherently data-driven, relying on detailed inventories of materials, energy use, and emissions across a product or building's lifecycle. However, this data is often subject to uncertainty due to factors such as variability in material production processes, gaps in supply chain transparency, and regional differences in energy grids.

Despite these challenges, LCA is considered robust for several reasons. First, it follows international standards (e.g., ISO 14040/14044 and EN 15978) that provide a structured framework for conducting assessments, ensuring consistency and comparability across studies. Second, LCA allows for sensitivity analysis and uncertainty analysis, which help quantify the impact of data variability on the results and identify areas where improvements in data quality are needed. Third, the use of Environmental Product Declarations (EPDs) and other verified data sources enhances the reliability of LCA results, particularly for embodied carbon and energy use.

That said, the robustness of LCA is not absolute, and its effectiveness depends on the context and purpose of the assessment. For example, while LCA can provide valuable insights into the relative environmental performance of different materials or design strategies, it may not capture all site-specific or temporal variations. Therefore, LCA should be viewed as a dynamic tool that evolves with improvements in data quality and methodology, rather than a definitive measure of environmental impact.

While both approaches employ multi-criteria evaluation, LCA standards offer more detailed quantitative frameworks for measuring specific environmental indicators throughout all building life cycle stages. (Anand and Amor, 2017; Malmqvist et al., 2011).

The key building LCA standards in the United Kingdom are aligned with the international ISO standards and European EN standards. EN 15978 is the core European standard that outlines the methodology for assessing the integrated environmental performance of buildings using a life cycle approach, aligning with the ISO 14040/14044 framework (Anand and Amor, 2017; Malmqvist et al., 2011). It covers all stages of a building's life cycle, including product, construction, use, and end-of-life stages, and is adopted and published by the British Standards Institution (BSI) in the United Kingdom as BS EN 15978 (Malmqvist et al., 2011).

EN 15804 provides the product category rules (PCR) for developing Environmental Product Declarations (EPDs) for construction products and services, aligning with the ISO 14025 standard on principles and procedures for Type III environmental declarations (Anand and Amor, 2017; Malmqvist et al., 2011). It is adopted and published by BSI in the United Kingdom as BS EN 15804 (Malmqvist et al., 2011). The EPDs developed per EN 15804 enable consistent, comparable LCA data to be used in evaluating the environmental impacts of buildings under EN 15978, allowing the entire building supply chain, from product manufacturers to construction firms, to align with a harmonized LCA methodology (Anand and Amor, 2017; Malmqvist et al., 2011).

The interrelation between these standards creates a cohesive framework for applying LCA consistently across the construction sector in the United Kingdom, from products to whole buildings, enabling more comprehensive environmental evaluation and impact reduction strategies aligned with circular economy principles (Anand and Amor, 2017; Malmqvist et al., 2011).

While Life Cycle Assessment (LCA) and Whole Building Life Cycle Assessment (WBLCA) enable a more comprehensive evaluation of environmental impacts compared to traditional assessment methods like Green Building Rating Systems (GBRS), they are not without limitations. One key challenge is the lack of data for emerging environmental concerns, such as microplastics or embodied biodiversity, which are not yet fully captured in LCA frameworks. For example, WBLCA does not currently provide detailed insights into a building's contribution to microplastic pollution, which can arise from sources such as vehicle tyre wear during materials transport (part of the supply chain's material impacts) or synthetic building materials (Kole et al., 2017).

That said, LCA and WBLCA still represent a significant advancement in environmental evaluation because they provide a structured framework for assessing a wide range of impacts, including carbon emissions, energy use, water consumption, and material resource depletion. By following international standards (e.g., ISO 14040/14044 and EN 15978), LCA ensures that these impacts are evaluated consistently and transparently, even if some areas remain underdeveloped.

To address gaps in data coverage, LCA practitioners often use proxy data or scenario analysis to estimate impacts for which direct data is unavailable. For example, while WBLCA may not directly quantify microplastic emissions, it can still assess the environmental footprint of materials that contribute to microplastic pollution (e.g., synthetic polymers) and recommend alternatives with lower overall impacts. Additionally, ongoing research and data collection efforts are gradually expanding the scope of LCA to include emerging concerns, ensuring that the methodology evolves to meet new environmental challenges.

2.2 GBRS and the embodied carbon gap

While GBRS like BREEAM have driven some environmental improvements through their broad sustainability lens, they face several limitations in comprehensively addressing climate change and aligning with national emissions reduction targets (Lützkendorf, 2018).

A key issue is the multi-criteria approach taken by GBRS, which evaluates various sustainability aspects like energy, water, materials, and indoor environmental quality. As a result, environmental criteria specifically related to emissions and whole-building life cycle assessment (LCA) typically receive limited weightings, often under 6% (Schweber and Haroglu, 2014).

BREEAM has made it evident that this limited emphasis on emissions leads to a misalignment with environmental priorities. Moreover, some of the broader environmental impacts—such as ecosystem degradation, resource depletion, and human toxicity—have only become widely recognized due to frameworks like BREEAM. However, despite these insights, GBRS still fail to adequately reflect both the urgent challenge of climate change, and the full spectrum of environmental concerns identified through LCA. Consequently, the current framework continues to understate both immediate climate imperatives and longer-term sustainability challenges.

For resource depletion, WBLCA can assess the use of non-renewable resources (e.g., fossil fuels, minerals) and the associated environmental impacts, such as energy consumption and carbon emissions. However, it often relies on proxy indicators (e.g., abiotic depletion potential) rather than direct measurements of resource availability or ecosystem impacts (Guinée, 2002).

For ecosystem degradation, WBLCA includes indicators like land use change and water consumption, which can indirectly reflect impacts on ecosystems (Guinée, 2002). However, it does not yet fully capture the biodiversity impacts of material extraction or construction activities, as methodologies for assessing embodied biodiversity are still in development (UKGBC, 2024).

For human toxicity, WBLCA can evaluate the potential health impacts of emissions and chemical exposures during material production, construction, and building operation. However, these assessments are often based on generic data rather than site-specific conditions, which can introduce uncertainty.

Moreover, as voluntary, market-driven standards, the adoption of GBRS is often driven more by marketing benefits and corporate social responsibility objectives than by specific emissions reduction targets aligned with national climate goals (Schweber and Leiringer, 2012; Cidell, 2009). The lack of mandatory requirements and stringent emissions thresholds further limits their effectiveness as instruments for achieving climate mitigation objectives (Cole and Valdebenito, 2013).

Focusing specifically on BREEAM, studies have highlighted its limited focus on embodied carbon emissions from building materials and construction processes, which can account for a significant portion of a building's total carbon footprint (Aktas and Bilec, 2012). This "embodied carbon gap" represents a critical blind spot in BREEAM's evaluation criteria, as it fails to capture the full environmental impact of buildings across their life cycle (Pomponi and Moncaster, 2018). Furthermore, BREEAM lacks explicit alignment with the United Kingdom's statutory carbon budgets and net-zero emissions targets.

BREEAM was developed in 1990, at a time when operational carbon—emissions from energy use during a building's lifecycle—accounted for the majority of the built environment's carbon footprint. By establishing a framework for improving energy efficiency and reducing operational emissions, BREEAM played a transformative role in driving the construction industry toward more sustainable practices. Its emphasis on operational performance led to widespread adoption of energy-efficient technologies, better insulation, and renewable energy systems, significantly reducing the carbon footprint of buildings over their operational phase.

However, as buildings have become more energy-efficient due to regulatory advancements and technological innovations, embodied carbon—emissions from material production, construction, and end-of-life processes—has emerged as a blind spot in BREEAM's assessment framework. While BREEAM has introduced credits for sustainable materials and Environmental Product Declarations (EPDs), these remain a relatively small portion of the overall score, typically accounting for less than 10%. This limited focus on embodied carbon fails to reflect its growing significance, which now represents a substantial portion of a building's total lifecycle emissions.

This evolution highlights a broader challenge: BREEAM's success in addressing operational carbon has created a new situation where embodied carbon is the dominant concern, yet the system has not fully adapted to this shift. While BREEAM continues to play a valuable role in promoting sustainable building practices, its failure to prioritize embodied carbon represents a missed opportunity to address the current environmental priorities of the construction industry.

Another limitation of BREEAM is that it provides a one-time certification rather than ongoing monitoring and adjustment mechanisms to ensure buildings continue meeting changing emissions targets over their life cycle (Schweber and Leiringer, 2012; Cidell, 2009). This static approach fails to account for the dynamic nature of emissions and the need for continuous improvement to align with evolving climate goals.

While BREEAM certification is typically awarded after project completion, it requires designers to consider and gather data much earlier in the design process than would otherwise occur. This early engagement ensures that sustainability criteria inform key decisions throughout the project lifecycle, from concept design to construction. For example, BREEAM encourages the use of energy modelling, material selection, and water efficiency strategies during the design phase, which can be reassessed and refined as the project progresses.

On the other hand, WBLCA is often described as a continuous process because it assesses environmental impacts across the entire building lifecycle, from material extraction to end-of-life. However, it is important to note that WBLCA primarily data gathers and provides a basis for decision-making rather than continuously assessing performance in real time. For WBLCA to be effective as a decision-making tool, it must be integrated into the design process early, like BREEAM, so that its insights can inform actions before they are taken.

Ideally, BREEAM and Life Cycle Assessment (LCA) standards could play complementary roles, with BREEAM offering a comprehensive sustainability framework and LCA standards providing robust methodologies that can be integrated into BREEAM to strengthen its environmental evaluations (Anand and Amor, 2017; Malmqvist et al., 2011). However, this integrated approach has yet to be fully realized, limiting the effectiveness of BREEAM in achieving quantifiable climate targets (Illankoon et al., 2017; Frischknecht et al., 2015). Life Cycle Energy Assessment (LCEA), a specialised application of LCA focusing on energy-related impacts throughout a building's lifetime, has become increasingly important as the industry seeks to reduce both operational and embodied energy consumption.

Table 2 presents a comparison between GBRS and WBLCA approaches, highlighting fundamental differences in their assessment methodologies, temporal scope, and alignment with climate targets. This comparison reveals how each system addresses various aspects of building sustainability and their respective strengths in supporting environmental performance improvement.

Linking this discussion to the RIBA Plan of Work (PoW) provides a useful framework for understanding how BREEAM and WBLCA can complement each other. BREEAM's requirements align well with Stages 2–4 (Concept Design, Developed Design, Technical Design) of the RIBA PoW, where key sustainability decisions are made. While WBLCA can be considered from Stage 0 (Strategic Definition) and Stage 1 (Preparation and Brief), it is typically more relevant from Stage 2 onwards, when design details become more defined. During the early stages, other tools specifically developed for concept design comparison, such as carbon calculators or early-stage embodied carbon tools, can help evaluate broad design options. WBLCA can then be integrated at later stages to assess and optimize the lifecycle impacts as the project evolves. By combining the strengths of both systems, stakeholders can make more informed decisions that balance immediate sustainability goals with long-term environmental performance.

While WBLCA is increasingly seen as a valuable tool for quantifying and reducing a building's carbon footprint, there are currently no policies or legislation that directly link WBLCA to national or global climate targets. For example, initiatives like SCORS (Standardized Carbon Offsetting and Reduction Scheme) have been proposed to align building assessments with climate goals, but these remain conceptual and are not yet implemented as policy (Arnold et al., 2024).

WBLCA could be integrated into future building regulations or carbon budgeting frameworks to ensure that construction projects contribute to national and global emissions reduction goals.

In contrast, GBRS like BREEAM are more closely tied to existing policies and market-driven sustainability goals, though they often lack the quantitative rigor needed to fully align with climate targets. Therefore, while WBLCA is not currently mandated by policy, its potential to support climate goals makes it a critical area for future development and integration into regulatory frameworks.

The comparison between BREEAM and WBLCA, therefore, is not between two fully realised systems but between an existing framework (BREEAM) and a forward-looking approach (WBLCA) that has the potential to address broader environmental impacts as data and methodologies improve. While WBLCA may not yet be fully available in a holistic sense, its development represents an important step toward more comprehensive building assessments that align with evolving environmental priorities.

A key limitation of both Green Building Rating Systems (GBRS) like BREEAM and Whole Building Life Cycle Assessment (WBLCA) is the lack of mandatory requirements in most jurisdictions. While BREEAM is widely adopted in the United Kingdom and other regions, its use remains largely voluntary unless specified by local planning authorities or project stakeholders. Similarly, WBLCA is not currently mandated by policy, though it is increasingly recommended as a best practice for assessing and reducing a building's carbon footprint.

In the United Kingdom, some local planning authorities have begun to require BREEAM certification or equivalent sustainability standards as a condition of planning approval. However, these requirements are not consistent across all regions, and the level of enforcement varies. For example, some authorities may mandate

TABLE 2 Comparison of GBRS and WBLCA assessment characteristics.

Criteria	GBRS (e.g., BREEAM)	WBLCA
Focus	Operational energy consumption, water efficiency, materials, and indoor environmental quality	Full lifecycle, including embodied carbon and operational impacts
Assessment Period	Informs decisions throughout design and construction; certification after completion	Data gathering and analysis across all lifecycle stages; informs decisions early in design
Integration with RIBA PoW	Aligns with Stages 2–4 (Concept Design, Developed Design, Technical Design)	Can be integrated across all RIBA stages, from Stage 0 (Strategic Definition) to Stage 7 (In Use)
Decision-Making	Encourages early consideration of sustainability criteria	Provides data to support lifecycle-informed decisions

a minimum BREEAM rating (e.g., “Very Good”), while others may only encourage its use. This lack of uniformity limits the system’s effectiveness in driving widespread adoption and ensuring consistent environmental performance across projects.

WBLCA, on the other hand, faces even greater challenges in terms of policy integration. While it has the potential to support national and global climate targets, there are currently few mandatory requirements for WBLCA in building regulations or planning frameworks. This means that its use is largely driven by voluntary initiatives, such as corporate sustainability goals or project-specific requirements. As a result, WBLCA’s impact is currently limited to early adopters and forward-thinking projects, rather than being a standardised practice across the industry (Ministry of Housing, 2024).

Local planning authorities are increasingly mandating the assessment and reduction of embodied carbon in construction projects. For instance, Bath and Northeast Somerset Council has introduced Policy C/EC, which requires embodied carbon assessments for major and minor developments, setting specific targets for sub-structures, superstructures, and finishes. Residential buildings of four storeys or fewer must achieve less than 625 $kgCO_2e/m^2$, while those of five storeys or greater, along with non-residential schemes, must achieve less than 800 $kgCO_2e/m^2$ and 900 $kgCO_2e/m^2$, respectively (Bath and NorthEast Somerset Council, 2024).

Similarly, the City of London Corporation has developed Building Design Standards aimed at minimizing emissions across the full lifecycle of buildings, from design through to construction and onwards. These standards include considerations of whole life carbon and cost analysis, the use of low-impact materials, and the introduction of circular economy principles into building practices (City of London Corporation, 2024).

To address these limitations, there is a growing call for policy interventions that make both BREEAM and WBLCA mandatory in certain contexts. For example, integrating WBLCA into building regulations or requiring BREEAM certification for all new developments could significantly enhance their effectiveness in achieving sustainability goals. However, such measures would need to be carefully designed to balance environmental benefits with practical implementation considerations.

For instance, the United Kingdom government could introduce regulations requiring whole-life carbon assessments for all new buildings over a certain size, similar to the approach taken in France with its RE2020 regulations (Ministère de la Transition écologique, 2024). Similarly, local planning authorities could mandate a minimum BREEAM rating for all new developments, ensuring a consistent baseline for sustainability performance.

2.3 Quantitative evidence supporting assessment system limitations

Analysis of current building assessment approaches reveals compelling quantitative evidence supporting the need for methodological reform. The limited consideration of embodied carbon in Green Building Rating Systems (GBRS) is demonstrated through multiple independent analyses of credit weightings and achieved reductions. Braulio-Gonzalo et al.'s systematic analysis of 387 sustainability indicators shows that materials and embodied impacts account for just 10.9% of indicators averaged across systems (Braulio-Gonzalo et al., 2022). This finding is reinforced by Ismaeel’s (2018) examination of eleven rating systems, which revealed remarkably consistent patterns in materials-related criteria weightings: LEED (10.43%), BREEAM (10%), GSAS (10%), and GRIHA (8.82%) (Ismaeel, 2018). Olanrewaju et al. quantified this imbalance through detailed credit analysis, demonstrating that operational credits consistently outweigh embodied credits by approximately 3:1 - LEED allocates 38 points to operational *versus* 9 points to embodied impacts, BREEAM 34 *versus* 14 points, and Green Star NZ 32 *versus* 18 points (Olanrewaju et al., 2024).

The practical implications of this imbalance are evident in achieved carbon reductions. Mulya et al. (2024) found that even highest-level certifications achieve minimal embodied carbon improvements - GreenRE Platinum achieves only 2.95% reduction while LEED scenarios show just 1.05% improvement over baseline (Mulya et al., 2024). These findings demonstrate a systematic undervaluation of embodied carbon impacts across rating systems.

The superior comprehensiveness of Whole Building Life Cycle Assessment (WBLCA) is evidenced through multiple comparative metrics. Izaola et al. demonstrate that WBLCA enables evaluation of 19 distinct environmental impact categories beyond carbon emissions, revealing that buildings’ ecotoxicity indicators are “on average 4.5 times greater than that of GWP” (Izaola et al., 2023).

The statistical validity of this comprehensive approach is confirmed by Ismaeel's (2018) reliability analysis, showing Cronbach's Alpha values of 94.4% and 93.5% for midpoint and endpoint impact categories respectively (Ismaeel, 2018). Systems incorporating substantial WBLCA components, particularly Green Star NZ with 22% of credits devoted to life cycle assessment, achieve more holistic sustainability evaluation (Olanrewaju et al., 2024).

The growing significance of embodied carbon as operational performance improves is supported by clear numerical progression across certification levels. Mulya et al. document embodied carbon's share increasing from 9.87% in baseline scenarios to 13.4% under GreenRE Platinum and 25.1% under LEED Platinum certification (Mulya et al., 2024). This progression continues in high-performance scenarios, with Alvi et al. showing embodied carbon reaching 28% of total emissions (Alvi et al., 2023). Izaola et al. provide further validation, demonstrating embodied carbon's share increasing from 27.6% in base scenarios to 72.4% in high-efficiency Scenario 5, emphasizing how operational improvements consistently shift the relative importance toward embodied impacts (Izaola et al., 2023).

The misalignment between current assessment methods and climate targets is evidenced through both achieved reductions and methodological inconsistencies. Even the most aggressive LEED scenarios achieve only 65.1% total carbon reduction, while unconventional design approaches reach 62.7% (Mulya et al., 2024). Olanrewaju et al.'s cosine similarity analysis reveals significant inconsistencies between systems, with similarity scores ranging from 0.348 to 0.722 (Olanrewaju et al., 2024). This lack of standardization is further emphasized by Izaola et al.'s finding of variations between 284% and 1,044% in embodied carbon weight assessments for key structural materials, demonstrating fundamental inconsistencies in how systems approach carbon reduction targets (Izaola et al., 2023).

This collective quantitative evidence, drawn from multiple independent analyses using different methodological approaches, demonstrates both the limitations of current assessment methods and the potential benefits of more comprehensive evaluation frameworks. The consistency of findings across studies strengthens the case for systematic changes to building assessment approaches as the industry moves toward more stringent climate targets.

2.4 Limitations and challenges in building LCA

There are many challenges faced in conducting building LCA that are often described by the various studies in the literature, these challenges can be classified in 3 categories, methodological challenges, building complexity and data challenges and finally workflow challenges involving software, tools and management of uncertainty.

Marsh et al. identified some of these challenges as functional unit definition, uncertainty in scenario prediction for the in-use and end-of-life of a building and predicting the lifetime of products and the building itself (Marsh et al., 2023).

Feng et al. observed three main challenges impacting the application of LCA to buildings, the variances in LCA goal and scope development, the complexity of building structures and the database variance in impact assessment (Feng et al., 2022). Fnais et al. mention some of the major current challenges in current LCA methods to include site-specific considerations, model complexity and scenario uncertainty (Fnais et al., 2022).

Conducting Whole Building Life Cycle Assessment (WBLCA) involves addressing two distinct but interrelated challenges: building complexity and data challenges. Building complexity refers to the intricate interactions between various systems, materials, and components within a building, which can make it difficult to model and assess environmental impacts accurately. For example, the interplay between structural systems, HVAC systems, and building envelopes requires detailed modelling to capture their combined effects on energy use and carbon emissions.

Data challenges, on the other hand, stem from the lack of comprehensive, high-quality data needed to conduct robust WBLCA. This includes gaps in data on material production processes, supply chain impacts, and end-of-life scenarios. For instance, while Environmental Product Declarations (EPDs) provide valuable data on embodied carbon, they often lack information on biodiversity impacts or social sustainability, limiting the scope of WBLCA.

A critical aspect of WBLCA that requires further discussion is the definition of system boundaries, particularly around the supply chain. While WBLCA typically focuses on the environmental impacts within the boundaries of a specific project, it often fails to account for broader supply chain dynamics. An example is the use of GGBS (Ground Granulated Blast-furnace Slag), a supplementary cementitious material that reduces the carbon footprint of concrete. While increasing the use of GGBS in one project may improve its WBLCA impact, it can reduce the availability of GGBS for other projects, resulting in no net environmental benefit. This issue, known as resource displacement, highlights the importance of considering supply chain impacts when defining system boundaries.

The Institution of Structural Engineers (IStructE) provides valuable guidance on addressing these challenges, particularly in relation to material selection and system boundaries. For example, the IStructE emphasizes the need to consider resource availability and supply chain constraints when assessing the environmental impact of materials like GGBS (Gibbons, 2022). By incorporating these insights, WBLCA can move beyond project-specific assessments to consider the broader implications of material use and resource allocation.

For instance, when assessing the environmental impact of concrete, WBLCA could incorporate data on the regional availability of materials like GGBS and the carbon intensity of their production and transportation. This would provide a more accurate picture of the material's true environmental impact, accounting for supply chain constraints and resource displacement.

There are a series of methodological issues that are embedded in the characteristics of the LCA process that affect building LCA outcomes and lead to high variation in assessment results. Säynäjoki et al. structured their analysis of these methodological differences through the four steps of the ISO 14040 framework to investigate decisions in each step that "profoundly affect the assessment outcome but are not sufficiently guided by the standard" (Säynäjoki et al., 2017).

2.4.1 Goal and scope

Säynäjoki et al. demonstrated that narrowly focused studies—for example, those analysing only core materials or specific building components—often yield environmental impact estimates at the lower end of the range reported in existing research. They emphasised that while such studies can be methodologically sound, their limited scope (e.g., excluding transportation, secondary materials, or construction processes) can lead to underestimations compared to broader assessments (Säynäjoki et al., 2017).

The authors observe that studies that excluded the construction site reported emissions well below the average. The study also identified that technical building equipment are often left out of assessments but are significant contributors to emissions as studies that include them typically rank among the highest end of reported emissions.

The functional unit is another important but often overlooked aspect in the goal and scope step of a building LCA. Aside from the ISO definition, EN 15978 standard introduced a functional unit intended to give a representation of the required technical characteristics and functionality of the building being assessed, including building type, required service life, relevant technical and functional requirements and pattern of use. Yet, Cabeza et al. observe there is no agreement on the functional unit considered in LCA or LCEA of buildings and it is often not mentioned in the studies making comparative exercises difficult (Cabeza et al., 2014).

2.4.2 System boundary

The system boundary definition in Building LCA is still a central challenge. Dixit et al. acknowledge that studies select system boundaries subjectively and describe three ways that system boundaries vary across studies (Dixit et al., 2012). The first is where studies only include one to a few life cycle stages of the building in their analysis, the second concerns the unclarity on how far upstream and downstream of each life cycle a study should go and the final regards all studies not considering the whole building but covering one or a few buildings components. These system boundary differences introduce problems of variation and incompleteness arising from exclusion of important life cycle stages or building components.

Pomponi and Moncaster observed that over 90% of building LCA studies they reviewed looked at the manufacturing stages whereas just over 50% go up to the end of the construction stage whilst the end-of-life stages are often totally overlooked (Pomponi and Moncaster, 2016).

The system boundary definition is a crucial step in LCA and the difference in boundaries across studies in the literature contribute to their incomparability yet there is no agreement in the literature on a standard system boundary model and what inputs should be included in a life cycle impact study.

2.4.3 Life cycle inventory

It has also been noted that different LCA studies might have similar boundary definitions but greatly different extensiveness in their Life Cycle Inventory (LCI). The challenges of compiling a comprehensive LCI for building LCAs is immense as thousands of items comprise a modern building and the construction processes are typically distributed among several contractors. Another issue noted at the LCI stage is that they are only described briefly which is a barrier to interpreting the results and drawing reliable conclusions.

Differences in sectoral emission intensities between the leading databases is a highly influential factor in variances in building LCA results. There is also concern regarding studies that utilise intensity factors from literature and other sources as in some cases the values are not even of the same magnitude as those from the most widely used databases although this might be because these intensity factors better represent local conditions. Sinha et al. also emphasised that it is important to exercise care in the use of commercial software tools when applying them to specific contexts situationally and geographically (Sinha et al., 2016).

2.4.4 Life cycle impact assessment and quantification

In quantifying the environmental impacts for building materials and components in Hong Kong, Chau et al. (Chau et al., 2015) observed that most databases were developed for applications in European countries and the building and construction processes pertained to the European context (Prior, 1993). The authors decided to localise the data as they found the database data unsuitable for direct application to LCA of buildings in Hong Kong. The localisation process involved (1) the replacement of the fuel mix for electricity generation assumed in the database with those used in the individual countries, (2) inclusion of the impacts incurred by transportation of the components and materials from their respective countries of origin to Hong Kong and (3) inclusion of the impacts incurred by local construction activities including construction processes, auxiliary materials and wastage during local construction activities.

Lai et al. note that the existing reviews in literature are primarily concerned with what has been done in building LCA related studies rather than how it can be done and expressed the need for innovations to improve the current quantification process (Lai et al., 2023). The study focused on identifying the process and information required for lifecycle carbon emissions quantification to improve reliability and accuracy in calculating emissions.

The LCIA process of LCA studies were observed to utilise LCA software like GaBi and SimaPro that combine databases and method compilations, but the accuracy of these software analyses is contested as they do not contain local data for all materials or production conditions. Cavalliere et al. note that the LCA of buildings is a complex task because of the large amount of information required and the time-consuming nature of the method and that predefined datasets for the materials and components are utilised in most cases, merging the LCI and LCIA into one step and simplifying the process (Yates et al., 1998).

2.4.5 Decision-making

The desired outcome of Building LCA is often cited to be decision-making, and the nature of these decisions are broadly categorised into decisions taken at the building scale or the material or component level. Having overviewed the current LCA methods, Fnais et al. presented important limitations and gaps that can be summarised to centre around three clusters, (1) decision support capabilities, (2) lack of alignment with domain models such as Building Information Modelling (BIM) and LCA data structures and (3) lack of full support of temporal information (Fnais et al., 2022).

Although a great number of works present outcomes of whole building LCAs, comparative studies and reviews on the topic, whole building life cycle has not been explicitly defined in the literature. Rodrigues and Simonen define Whole building LCA as “an LCA exercise where the entire building project is considered holistically to help building designers focus their efforts when a reduced footprint is desired” (Huang et al., 2019).

The scope definition in context of the EN considered usually determines whether a cases study classifies as whole building LCA - that is it considers the whole life cycle of building (cradle-to-site + use + end of life) - although many studies considered whole building LCAs do not include end of life.

The LCA at the building scale is commonly conducted at the end of the design process when the necessary information is available, but it is too late to affect the decision-making process, a dilemma rooted in the nature of the design process.

The need to integrate Life Cycle Assessment (LCA) into the design process has been highlighted by researchers and practitioners alike. However, it is important to recognize that building design is a multidisciplinary endeavour, involving architects, structural engineers, MEP (mechanical, electrical, and plumbing) engineers, sustainability consultants, quantity surveyors, and other stakeholders. Each discipline plays a critical role in shaping the environmental performance of a building, from material selection and structural efficiency to energy systems and operational strategies.

For example, structural engineers are responsible for optimising material use and minimising embodied carbon, while MEP engineers design systems that reduce operational energy consumption. Sustainability consultants provide expertise on LCA methodologies and environmental performance metrics, ensuring that design decisions align with broader sustainability goals. By involving all relevant disciplines early in the design process, project teams can leverage their collective expertise to optimize the building’s environmental performance and ensure that LCA insights inform decision-making at every stage.

That said, challenges remain in integrating LCA into the multidisciplinary design process. For instance, architects and engineers may have different priorities or levels of familiarity with LCA methodologies, which can lead to misalignment or missed opportunities for optimization. To address this, there is a growing need for interdisciplinary collaboration and training programs that equip all stakeholders with the knowledge and tools needed to effectively incorporate LCA into their work (Hollberg et al., 2020).

The relationship between GBRS and LCA standards presents opportunities for complementary application, with GBRS providing comprehensive sustainability frameworks and LCA standards offering robust methodologies for environmental evaluation. However, this integrated approach remains incompletely realised, limiting the effectiveness of building assessment in achieving quantifiable climate targets.

3 Advanced modelling techniques

This section discusses advanced techniques to improve whole building life cycle assessment, focusing on two main areas: Building Information Modelling (BIM) Integration, and Automated Data Collection and Machine Learning. These techniques aim to overcome limitations in conventional life cycle assessment methods by streamlining data collection processes, improving accuracy and completeness of assessments, enabling continuous monitoring and optimisation throughout a building’s lifecycle, and providing more comprehensive and data-driven decision-making tools.

By combining these approaches, stakeholders can make more informed decisions based on holistic environmental impact assessments, aligning with evolving climate targets and sustainability goals.

3.1 Building Information Modelling (BIM) integration

BIM has emerged as a transformative advanced technique to overcome several limitations in sustainable building assessment systems. By seamlessly integrating BIM with whole building life cycle assessment (WBLCA), this approach addresses data availability, complexity, and embodied carbon challenges, while enhancing decision-support capabilities.

3.1.1 Addressing data availability and complexity challenges

One of the major barriers to widespread adoption of WBLCA has been the extensive data requirements and the complexity of data collection processes (European Commission, 2021). BIM platforms offer a comprehensive and structured digital representation of a building, containing detailed information about its components, materials, quantities, and specifications (Howard, 1990). By leveraging this data-rich resource, BIM-integrated WBLCA can streamline the data collection process, reducing the time and effort required for manual data entry (HM Government, 2021).

When describing Building Information Modelling (BIM) as a comprehensive tool for sustainable building assessment, it is important to clarify that no BIM model captures all information about a building. Instead, BIM provides a structured and detailed digital representation of a building’s components, materials, and systems, which can be continuously updated as the project progresses. However, the level of detail and accuracy in a BIM model depends on the stage of the project and the information available at that time. For example, during RIBA Stage 2 (Concept Design), the BIM model may include only basic geometric and material data, while by RIBA Stage 5 (Construction), it can incorporate detailed information on M&E (mechanical and electrical) systems as delivered by the contractor.

The RIBA Plan of Work (PoW) provides a useful framework for understanding how BIM supports decision-making at different stages of a project (RIBA, 2020). During Stage 2 (Concept Design), BIM can be used to explore design alternatives and assess their environmental impacts, even though the model may not yet include detailed information on M&E systems or construction methods. By Stage 4 (Technical Design), the BIM model becomes more comprehensive, enabling more accurate assessments of embodied carbon, energy use, and other environmental impacts.

Finally, during Stage 7 (In Use), the BIM model can be updated with as-built data and operational performance information, supporting ongoing optimization of the building’s environmental performance. However, it is important to recognize that BIM's effectiveness as a decision-making tool depends on the timeliness and quality of the information available at each stage. For instance, during RIBA Stage 2 (Concept Design), BIM can be used to compare the embodied carbon of different structural systems, such as steel *versus* concrete, even though detailed information on M&E systems is not yet available. By Stage 4 (Technical Design), the BIM model can incorporate detailed data on material specifications and construction methods, enabling more accurate assessments of environmental impacts. Finally, during Stage 7 (In Use), the BIM model can be updated with real-time energy use data, supporting ongoing optimization of the building's operational performance.

The integration of Building Information Modelling (BIM) with Whole Building Life Cycle Assessment (WBLCA) has the potential to create a seamless flow of data across the building lifecycle, from design and construction to operation and end-of-life. However, it is important to recognize that this seamless flow is currently more of a future aspiration than a present reality. In practice, achieving seamless data integration faces several challenges, including interoperability issues, data silos, and inconsistent data standards.

For example, while BIM platforms can provide detailed information on materials, quantities, and specifications, this data often needs to be manually extracted and reformatted for use in LCA software. Similarly, real-time data from IoT-enabled sensor networks may not always integrate smoothly with BIM models, requiring additional effort to align and analyse the data. These challenges highlight the need for standardized data protocols and interoperable tools to enable true seamless data flow.

That said, the potential benefits of seamless data integration are significant. By enabling real-time updates and automated data extraction, BIM-integrated WBLCA could streamline the assessment process, reduce errors, and provide more accurate and timely insights into a building's environmental performance. While this vision is not yet fully realized, ongoing advancements in technology and data standards are gradually moving the industry closer to this goal.

For instance, the development of open data standards like IFC (Industry Foundation Classes) and COBie (Construction Operations Building Information Exchange) could enable smoother data exchange between BIM platforms and LCA software (BuildingSMART International, 2024). Similarly, advancements in API (Application Programming Interface) technology could facilitate real-time data integration from IoT sensors into BIM models, supporting more dynamic and accurate environmental assessments.

3.1.2 Capturing embodied carbon emissions

One of the major limitations of GBRS like BREEAM is their limited focus on embodied carbon emissions from building materials and construction processes. BIM-integrated WBLCA directly addresses this "embodied carbon gap" by leveraging the comprehensive material and component data available in BIM models.

While Whole Building Life Cycle Assessment (WBLCA) provides a valuable framework for quantifying a building's environmental impacts, it is important to recognize that its results are inherently probabilistic rather than definitive. WBLCA relies on a combination of measured data, assumptions, and modelling techniques to estimate impacts, which introduces a degree of uncertainty. To address these challenges, it is essential to provide a clearer understanding of the level of confidence associated with WBLCA results. This includes quantifying error bars or uncertainty ranges.

Furthermore, WBLCA practitioners should prioritise the use of high-quality, verified data sources, such as Environmental Product Declarations (EPDs), and clearly document any assumptions or limitations in their assessments. By adopting a more transparent and probabilistic approach, WBLCA can provide more reliable and actionable insights, even in the face of uncertainty.

3.1.3 Enabling iterative design optimisation

The integration of BIM and WBLCA facilitates iterative design optimisation throughout the building's life cycle. BIM models can be used to explore and evaluate various design alternatives, material choices, and construction methods, providing real-time feedback on the environmental impacts of each scenario.

This iterative process allows design teams to identify and mitigate environmental hotspots, explore trade-offs between different impact categories, and optimize the building's performance based on quantitative data.

Therefore, while continuous assessment has value in certain contexts, the early stages of design are the most critical for addressing embodied carbon and other irreversible impacts. By integrating Whole Building Life Cycle Assessment (WBLCA) into the design process, project teams can make informed decisions that minimise potential impacts before construction begins, reducing the risk of costly or impractical changes later.

The integration of iterative design optimization approaches with Whole Building Life Cycle Assessment (WBLCA) represents an opportunity to enhance building sustainability through multi-objective optimization techniques. Traditional structural optimization approaches that focus solely on minimum weight have been shown to result in substantial material inefficiencies. As demonstrated by Cucuzza et al., conventional minimum-weight optimization for steel structures can result in a waste-to-structure mass ratio (Mwaste/Mtruss) of 147% for a Warren truss case study, highlighting the limitations of single-objective optimization approaches (Cucuzza et al., 2024).

To address these inefficiencies, cutting stock optimization (CSP) can be integrated within the structural design process. Cucuzza et al. demonstrated that incorporating CSP into the optimization framework reduced the waste-to-structure mass ratio to 21% for the same Warren truss case study, while maintaining structural performance requirements (Cucuzza et al., 2024). This significant improvement illustrates the potential for iterative optimization techniques to bridge the gap between theoretical design efficiency and practical construction constraints.

The environmental implications of such integrated approaches can be assessed through Life Cycle Assessment. In their analysis of a spatial reticular dome, Cucuzza et al. found that with their CSP approach, 83% of the environmental impact was attributable to steel profiles being transported to and used in the construction site, while in the minimum weight approach, 45% of the impact was allocated to scrap steel sections requiring reprocessing or recycling (Cucuzza et al., 2024). The cutting process itself had relatively minor impacts on the overall environmental performance.

A key innovation in this approach is the integration of construction-phase considerations into early design optimization. Rather than treating constructability as a post-design consideration, Cucuzza et al. demonstrated that incorporating fabrication constraints and material utilization metrics directly into the optimization process can achieve significant waste reduction. For example, in their reticular dome case study, the CSP approach achieved a waste-to-stock ratio (Mwaste/Mstock) of 14%, compared to 24.7% for the traditional minimum-weight approach.

The methodology employed suggests promising directions for future development of WBLCA optimization frameworks. The research demonstrates the successful application of genetic algorithms combined with cutting stock optimization, providing a foundation for handling complex multi-objective optimization problems that incorporate both environmental impact categories and practical construction constraints.

Furthermore, the research emphasizes the importance of considering both structural efficiency and material waste. Cucuzza et al. found that while minimum-weight approaches may achieve lower structural mass, the resulting material waste can offset these gains from an environmental perspective. This suggests the need for optimization frameworks that can address multiple performance criteria simultaneously.

The effectiveness of combining different optimization techniques has been demonstrated through the case studies. Cucuzza et al. successfully integrated genetic algorithms for global optimization with cutting stock optimization for specific fabrication constraints. This hybrid approach offers potential for WBLCA applications, where different aspects of building performance and environmental impact may require different optimization strategies.

These findings suggest that the future of building design lies in integrated frameworks that can simultaneously address multiple objectives while respecting practical construction constraints. Such approaches enable designers to develop solutions that are both environmentally optimal and constructible, advancing the practical application of WBLCA in building design and construction.

3.1.4 Supporting informed decision-making

The integration of BIM and WBLCA creates a powerful decision-support framework that overcomes the limitations of both GBRS and conventional LCA approaches. BIM models provide a comprehensive and visually intuitive representation of the building, while WBLCA quantifies the associated environmental impacts.

By combining these complementary data sources, stakeholders can make informed decisions based on a holistic understanding of the building's design, materials, construction processes, and their corresponding environmental impacts. This integrated approach handles the limitation GBRS faces of having a wide focus across multiple sustainability criteria but lacking the depth needed to address emerging concerns like embodied carbon. WBLCA, on the other hand, provides a more detailed and quantitative assessment of specific environmental impacts, making it a valuable complement to GBRS rather than a replacement (Illankoon et al., 2017; Lützkendorf, 2018).

To illustrate the holistic decision-support capabilities of BIM and Whole Building Life Cycle Assessment (WBLCA), consider the case of the One Angel Square building in Manchester, UK (BAM Construct and Ventures UK Ltd, 2024). This project utilised BIM and WBLCA to evaluate and optimise the building's environmental performance across multiple criteria (UK BIM Framework, 2024), including embodied carbon, operational energy use, water efficiency, and indoor environmental quality (BAM Construct and Ventures UK Ltd. 2014).

During the design phase, the project team used BIM to create a detailed digital model of the building, which included information on materials, systems, and energy performance. This model was integrated with WBLCA to assess the environmental impacts of different design options, enabling the team to make informed decisions that balanced multiple sustainability goals. For example, the team compared the embodied carbon of different structural systems (e.g., steel vs concrete) and selected the option with the lowest lifecycle impact. They also optimised the building's energy performance by simulating different HVAC systems and insulation materials, ensuring that operational energy use was minimized without compromising indoor comfort.

The integration of BIM and WBLCA also supported decisions related to water efficiency and indoor environmental quality. For instance, the team used BIM to model rainwater harvesting systems and low-flow fixtures, which were evaluated using WBLCA to ensure they contributed to the building's overall sustainability goals. Similarly, the team assessed the impact of different materials on indoor air quality, selecting low-emission products that improved occupant health and wellbeing.

By leveraging BIM and WBLCA, the One Angel Square project achieved BREEAM Outstanding certification, demonstrating how these tools can support holistic decision-making across multiple sustainability criteria (BAM Construct and Ventures United Kingdom Ltd.). This example highlights the potential of BIM and WBLCA to address the limitations of traditional assessment methods like BREEAM, which often focus on individual criteria rather than providing a comprehensive evaluation of environmental performance.

While BIM-integrated Whole Building Life Cycle Assessment (WBLCA) is described as a comprehensive tool for assessing environmental impacts, it is important to clarify that its current capabilities are primarily focused on carbon emissions, including both embodied carbon (from materials and construction) and operational carbon (from energy use during the building's lifecycle). At present, BIM-integrated WBLCA does not yet cover a wide variety of environmental impacts, such as water use, biodiversity, or toxicity, due to limitations in data availability and methodological frameworks.

Furthermore, BIM-integrated WBLCA can be coupled with other advanced techniques, such as multi-criteria decision analysis (MCDA) and uncertainty analysis, to further enhance its decision-support capabilities (Buyle et al., 2013; Robati et al., 2016; Obrecht et al., 2024). By incorporating economic, social, and stakeholder preferences alongside environmental impacts, this integrated approach provides a comprehensive framework for evaluating trade-offs and making balanced decisions aligned with sustainable development principles (Illankoon et al., 2017; Robati et al., 2016).

3.2 Automated data collection and machine learning

3.2.1 Automated data collection and real-time monitoring

One of the major bottlenecks in conducting comprehensive whole building life cycle assessment (WBLCA) is the extensive data collection required across the building's entire life cycle, from material extraction to construction, operation, and end-of-life phases (Buyle et al., 2013). Traditional methods rely on manual data gathering, which can be time-consuming, resource-intensive, and prone to errors or incomplete information.

(Buyle et al., 2013) While IoT (Internet of Things) technology holds significant potential for enhancing Whole Building Life Cycle Assessment (WBLCA), it is important to recognize that its current applications are still in the early stages of development. IoT-enabled sensors can provide real-time data on energy use, occupancy patterns, and environmental conditions, which can be used to improve the accuracy of WBLCA and support ongoing optimization of a building's performance. However, the practical implementation of IoT in building assessments faces several challenges, including data delays, feedback loop limitations, and the complexity of integrating IoT data with existing assessment frameworks.

For example, the Edge building in Amsterdam, Netherlands, uses IoT sensors to monitor energy consumption, indoor air quality, and occupancy levels in real time. This data is integrated with the building's BIM (Building Information Modelling) system to provide insights into operational performance and identify opportunities for improvement (BRE Group, 2024). However, even in this advanced example, there are delays in data processing and feedback, which can limit the effectiveness of real-time optimization. Additionally, the integration of IoT data with WBLCA requires significant effort to ensure data accuracy and consistency, as IoT sensors may produce large volumes of data that are not always directly applicable to lifecycle assessments.

Another example is the Bullitt Centre in Seattle, USA, which uses IoT sensors to monitor energy and water use, as well as indoor environmental conditions (Bullitt Foundation, 2024). While this data has been valuable for optimizing the building's operational performance, it has not yet been fully integrated into a WBLCA framework to assess lifecycle impacts. This highlights the gap between the theoretical potential of IoT and its current practical applications in building assessments.

While IoT (Internet of Things) technology has the potential to provide continuous and accurate data for building performance monitoring, it is important to recognize that the reliability and accuracy of IoT data can vary significantly depending on the quality of sensors, data transmission methods, and environmental conditions. Studies have shown that IoT sensors can achieve high levels of accuracy under controlled conditions, but their performance may degrade in real-world applications due to factors such as sensor drift, interference, and data transmission delays.

For example, a study by Zanella et al. on IoT applications in smart buildings found that while IoT sensors can provide real-time data on energy use and environmental conditions, the accuracy of this data is often affected by calibration errors and signal noise, leading to error margins of ±5%–10% in some cases (Zanella et al., 2014). Similarly, research by Gubbi et al. highlights the challenges of ensuring data reliability in IoT systems, particularly in large-scale deployments where thousands of sensors may be operating simultaneously (Gubbi et al., 2013). These studies underscore the need for regular calibration, data validation, and error correction to ensure the accuracy and reliability of IoT data (Gubbi et al., 2013).

In practice, the reliability of IoT data also depends on the specific application and environment. For instance, IoT sensors used to monitor indoor air quality may be affected by factors such as humidity and temperature fluctuations, which can introduce errors into the data. Similarly, sensors used to measure energy consumption may be influenced by voltage fluctuations or electromagnetic interference, further complicating data accuracy.

3.2.2 Machine learning for pattern recognition and predictive modelling

The vast amounts of data generated through automated collection processes can be leveraged by machine learning algorithms to identify patterns, trends, and insights that would be challenging to detect through manual analysis (Buyle et al., 2013). Machine learning techniques can be applied to historical data, including building energy usage, material consumption, and environmental impacts, to develop predictive models and forecast future scenarios.

These models can be used to optimise building operations, predict maintenance requirements, and inform design decisions aimed at minimizing environmental impacts throughout the building's life cycle (Buyle et al., 2013). Additionally, machine learning algorithms can be trained on real-world data to improve the accuracy and reliability of life cycle impact assessments, addressing the limitations of conventional LCA approaches that often rely on generic or outdated data sources.

The application of machine learning (ML) to building performance data sets has the potential to enhance the accuracy and efficiency of Whole Building Life Cycle Assessment (WBLCA). However, the effectiveness of ML depends on several factors, including data ownership, data reliability, and data sharing mechanisms. In most cases, building performance data is owned by building operators, utility companies, or third-party service providers, who may have varying levels of willingness to share this data. For example, utility companies often collect detailed energy use data, but access to this data may be restricted due to privacy concerns or commercial interests. Similarly, building operators may be reluctant to share data due to concerns about data security or competitive advantage.

The reliability of the data used for ML applications is another critical factor. As discussed earlier, IoT sensors and other data collection methods can introduce errors due to sensor drift, calibration issues, and environmental factors. Studies such as Zanella et al. and Gubbi et al. have highlighted the challenges of ensuring data accuracy in IoT systems, which can affect the performance of ML algorithms (Zanella et al., 2014; Gubbi et al., 2013). Therefore, data used for ML applications must be carefully validated and cleaned to ensure its reliability.

Regarding data sharing, there are ongoing efforts to develop standardized protocols and data-sharing frameworks that enable secure and efficient sharing of building performance data. For example, the Building Data Exchange (BDX) initiative aims to create a platform for sharing building performance data across stakeholders, while ensuring data privacy and security (BuildingLogiX Data eXchange, 2024). However, these initiatives are still in the early stages of development, and widespread adoption remains a challenge. The Building Data Exchange (BDX) initiative uses blockchain technology to create a secure and transparent platform for sharing building performance data (BuildingLogiX Data eXchange, 2024). This approach ensures that data is shared only with authorised stakeholders, while maintaining privacy and security.

3.2.3 Artificial intelligence for intelligent decision support

Artificial intelligence (AI) techniques, such as expert systems and decision support tools, can be integrated with WBLCA to provide intelligent decision support capabilities. AI-powered systems can analyse complex environmental, economic, and social data, identify patterns and relationships, and generate actionable insights to support decision-making processes.

These AI-driven decision support tools can assist stakeholders in navigating trade-offs between different environmental impact categories, identifying optimal design alternatives, and developing strategies for minimizing the overall environmental burden throughout the building's life cycle (Buyle et al., 2013). By combining the quantitative power of WBLCA with the intelligent decision-making capabilities of AI, this approach overcomes the limitations of GBRS and conventional LCA, which often struggle to provide comprehensive and balanced decision support.

Although AI has the potential to address some of the limitations of LCA and GBRS, it is important to recognize that AI is only as effective as the data it is trained on and the algorithms it uses. AI can analyse large datasets and identify patterns that may not be apparent through manual analysis, but its effectiveness depends on the quality, completeness, and reliability of the data. For example, AI has been used in other fields to optimize complex systems, such as energy grids and supply chains, as demonstrated by Zhang et al. in their study on AI-driven energy optimization (Zhang et al., 2022). However, applying AI to building assessments requires high-quality data on material properties, production processes, and transportation, which may not always be available.

One of the key challenges in using AI for building assessments is the uneven development of datasets across different environmental criteria. For instance, while datasets on embodied carbon are relatively well-developed, data on embodied biodiversity or social sustainability is still in its infancy. This imbalance can lead to biased decisions, as AI algorithms may prioritize areas with more robust data, potentially overlooking important but less well-documented impacts. Additionally, AI systems can be manipulated if the input data is biased or incomplete, leading to perverse outcomes where decisions are optimized based on data reliability rather than overall environmental impact.

To address these challenges, it is essential to establish rigorous data quality assurance (QA) processes and transparent decision-making frameworks for AI applications. For example, sensitivity analysis can be used to assess the impact of data uncertainty on AI-driven decisions, while multi-criteria decision analysis (MCDA) can help balance competing objectives and ensure that decisions are based on a holistic understanding of environmental impacts. However, these approaches require significant research and development to be effectively integrated into AI systems (Saltelli et al., 2019; Huang et al., 2011; Torkayesh et al., 2022).

3.2.4 Integration with building information modelling (BIM) and digital twins

Automated data collection, machine learning, and AI techniques can be seamlessly integrated with Building Information Modelling (BIM) and digital twin technologies, creating a powerful synergy for sustainable building assessment (Santos et al., 2019). BIM platforms provide a data-rich digital representation of the building, enabling the integration of WBLCA and real-time monitoring data.

Digital twins—virtual representations of physical buildings—have the potential to enhance Whole Building Life Cycle Assessment (WBLCA) by providing real-time data and enabling continuous optimisation, it is important to recognize the complexity and dynamic nature of building systems.

Digital twins rely on real-time data from IoT sensors, BIM models, and other sources to simulate and predict building performance. However, the stages of construction, system complexity, and feedback cycles introduce significant challenges that must be addressed to ensure the effectiveness of digital twins.

During the construction phase, decisions are made that have long-lasting impacts on a building's environmental performance. For example, material selection, construction methods, and system installations are critical to minimizing embodied carbon and ensuring energy efficiency. However, digital twins often struggle to capture the dynamic and iterative nature of these decisions, as data from the construction site may be incomplete, delayed, or inconsistent. This can lead to non-linear and chaotic outcomes, where small changes in input data result in disproportionately large or unpredictable impacts on the digital twin's predictions.

The complexity of building systems further complicates the use of digital twins. Buildings are composed of interconnected systems (e.g., structural, mechanical, electrical) that interact in ways that are not always well understood. As highlighted in Meadows's *"Thinking in Systems"*, complex systems often exhibit feedback loops and emergent behaviours that are difficult to model accurately (Meadows, 2008). For instance, changes to the HVAC system may affect indoor air quality, energy use, and occupant comfort in ways that are not immediately apparent. Digital twins must account for these interactions to provide meaningful insights, but this requires a level of data integration and system understanding that is not yet fully realized.

Moreover, the feedback cycles inherent in building systems can lead to non-sensical outcomes if not properly managed. For example, a digital twin might recommend optimizing energy use by reducing ventilation rates, but this could lead to poor indoor air quality and occupant discomfort. Balancing competing objectives and ensuring that feedback loops are accurately modelled is essential to avoid such perverse outcomes.

For instance, a digital twin might recommend increasing the use of natural ventilation to reduce energy consumption, but this could lead to higher indoor temperatures and increased cooling demand in warmer climates. Such feedback loops must be carefully modelled to avoid unintended consequences (Clausen et al., 2021; Yan et al., 2015).

By leveraging automated data collection, machine learning, and AI techniques, combined with BIM integration and digital twin technologies, the advanced WBLCA approach can overcome the limitations of conventional assessment systems.

3.3 Limitations of advanced techniques

The integration of advanced technologies such as Building Information Modelling (BIM) and machine learning (ML) into the construction industry holds immense potential for improving efficiency, reducing costs, and enhancing project outcomes. However, the adoption of these technologies is fraught with significant challenges, ranging from technical and financial barriers to cultural resistance and regulatory complexities. Addressing these challenges requires a nuanced understanding of the industry's unique dynamics and a strategic, phased approach to implementation.

One of the most prominent challenges is the high initial cost associated with adopting BIM and ML technologies. The construction industry, particularly small and medium-sized enterprises (SMEs), often operates on thin profit margins, making substantial investments in software, hardware, and training financially burdensome (Azhar et al., 2011). Furthermore, the lack of a skilled workforce proficient in these technologies exacerbates the problem. Many construction professionals lack the digital literacy required to effectively utilize BIM and ML tools, and resistance to change further impedes adoption (Pan and Zhang, 2021). This resistance is often rooted in the industry's traditional risk-averse culture, where established practices are preferred over innovative but unfamiliar workflows (Turner, 2007).

Data fragmentation and interoperability issues also pose significant barriers to the successful implementation of BIM and ML. Construction projects typically involve multiple stakeholders, each using different software systems, which leads to data silos and inefficiencies (Succar, 2009). For BIM and ML to deliver their full potential, seamless data integration and interoperability are essential. However, the absence of standardized data formats and protocols often hinders this integration (Forgues and Iordanova, 2010). Additionally, the quality and availability of data are critical for ML applications, which rely on large volumes of high-quality data to generate accurate predictions and insights. Inconsistent data collection practices and a lack of standardization in the industry further complicate the adoption of ML (Bilal et al., 2016).

Cultural resistance to change is another formidable obstacle. The construction industry has historically been slow to adopt new technologies, and the transition to digital workflows requires a significant shift in mindset (Bryde et al., 2013). Workers and managers accustomed to traditional methods may view BIM and ML as disruptive rather than beneficial. Overcoming this resistance necessitates a concerted effort to demonstrate the tangible benefits of these technologies, such as improved efficiency, reduced costs, and enhanced decision-making capabilities (Gerrish et al., 2017).

Regulatory and legal barriers further complicate the adoption of BIM and ML. The lack of clear standards and guidelines for BIM implementation can create uncertainty, particularly regarding liability and accountability (Zhang and El-Gohary, 2016). Data privacy and security concerns also arise with the use of ML systems, which often require access to sensitive project data. Addressing these issues requires collaboration with industry bodies and regulators to establish clear standards and ensure compliance with local and international regulations (Oesterreich and Teuteberg, 2016).

To overcome these challenges, a phased implementation strategy is recommended. The first phase should focus on pilot projects to demonstrate the value of BIM and ML on a small scale. These pilot projects can serve as proof of concept, allowing firms to identify potential challenges and build internal expertise (Azhar et al., 2011). The second phase should prioritize training and upskilling the workforce. Investing in targeted training programs and collaborating with educational institutions to develop tailored courses can help bridge the skills gap and improve digital literacy (Sacks et al., 2018). The third phase involves full integration, where BIM and ML are scaled across all projects. This phase requires the establishment of standardized workflows and protocols to ensure interoperability and consistency (Succar, 2009).

For ML specifically, the initial phase should focus on data collection and preparation. Standardizing data collection processes and leveraging sensors and IoT devices to gather real-time data from construction sites can ensure high-quality input for ML algorithms (Pan and Zhang, 2021). The second phase should involve piloting ML applications for specific use cases, such as predictive maintenance, cost estimation, or risk assessment. Evaluating the performance of these models and refining them based on feedback is crucial (Cao et al., 2017). The final phase entails scaling ML solutions across broader workflows, such as project scheduling and resource allocation, while continuously monitoring and updating the models to adapt to changing conditions (Bilal et al., 2016).

Addressing cultural resistance requires fostering a culture of innovation within organizations. Involving employees in the decision-making process and highlighting the benefits of BIM and ML can help gain buy-in (Turner, 2007). Providing ongoing support and mentorship can also ease the transition to new technologies. Additionally, collaboration with academic institutions and industry bodies can play a critical role in overcoming barriers and ensuring long-term success (Forgues and Iordanova, 2010).

3.4 Industry stakeholder dynamics in embodied carbon reduction

The reduction of embodied carbon in construction is a complex challenge that requires the coordinated efforts of a diverse network of stakeholders, including policymakers, industry professionals, educators, material suppliers, and practitioners. Each stakeholder group plays a distinct but interconnected role in driving the adoption of Whole Life Carbon Assessment (WBLCA) and fostering interdisciplinary collaboration for effective implementation. Their interrelations are critical to overcoming barriers and achieving meaningful progress in embodied carbon reduction.

3.4.1 Collaborative efforts and leadership

Professional bodies and organisations have emerged as key coordinators in aligning industry efforts. The London Energy Transformation Initiative (LETI, 2025a), in collaboration with RIBA, the Greater London Authority (GLA), the Institution of Structural Engineers (IStructE), and the UK Green Building Council

(UKGBC), has taken a leading role in developing standardized approaches to carbon assessment and target-setting. As noted in the *LETI Target alignment* document, "the industry needs to standardise performance and reporting scopes to meet IPCC recommendations for urgent emissions reductions" (LETI, 2025a). This collaboration reflects a shared recognition of the need for collective action to address the climate crisis.

IStructE Initiatives: IStructE has been instrumental in advancing embodied carbon reduction through its Climate Emergency Task Group, which has developed guidance and tools for structural engineers. Their *How to Calculate Embodied Carbon* guide provides a clear methodology for assessing the carbon footprint of structural materials, emphasizing the importance of early-stage decision-making to minimize carbon impacts (The Institution of Structural Engineers, 2024). IStructE also advocates for the reuse of existing structures and the specification of low-carbon materials, aligning with LETI's "Build Less" and "Build Collaboratively" strategies (*LETI One Pager*) (LETI, 2025b).

3.4.1.1 Policymakers and regulators

Policymakers and regulators are pivotal in establishing the framework for carbon reduction. Their ability to mandate performance standards, require disclosure, and create market incentives shapes the operating environment for all other stakeholders. For example, the GLA's London Plan requires major developments to submit a circular economy statement and a whole life carbon assessment, ensuring that carbon impacts are considered at every stage of a project (Greater London Authority, 2021).

Challenges: The effectiveness of policy interventions depends heavily on industry readiness and capability to implement new requirements. Fragmented responsibilities and misaligned incentives often hinder progress.

Strategies: Policymakers must focus on creating clear regulatory frameworks, providing financial incentives, and fostering industry-wide alignment on carbon reduction targets.

Röck et al. (2020) emphasize the importance of policy interventions in driving low-carbon practices, highlighting the need for consistent regulatory frameworks to ensure industry-wide adoption of WBLCA (Röck et al., 2020).

3.4.1.2 Clients and developers

Clients and developers are among the most influential stakeholders, as their project requirements and investment decisions directly impact carbon outcomes. Early client commitment to carbon targets drives downstream decisions throughout the project lifecycle. For instance, clients who mandate WBLCA and set specific performance targets enable design teams to prioritize carbon reduction from project inception.

Challenges: Clients often face competing pressures between carbon reduction goals and commercial considerations, underscoring the need for clear business cases and value propositions.

Strategies: Clients should establish clear carbon reduction targets, integrate WBLCA into procurement processes, and collaborate closely with design and construction teams.

Hart et al. highlight the critical role of client leadership in driving sustainable construction practices, emphasizing the need for early commitment to carbon reduction goals (Hart et al., 2019).

3.4.1.3 Design professionals

Design professionals occupy a critical position in translating high-level carbon objectives into practical solutions. Decisions made during early design stages can influence up to 80% of a building's lifetime carbon impact (Azari and Abbasabadi, 2018). However, designers' effectiveness depends heavily on having appropriate skills, tools, and data to evaluate carbon impacts.

Challenges: Significant knowledge gaps exist in areas such as embodied carbon assessment and low-carbon design strategies.

Strategies: Designers should prioritize early-stage carbon assessments, leverage tools like RICS Whole Life Carbon Assessment, and collaborate with material suppliers to identify low-carbon solutions.

Crawford and Stephan emphasise the critical role of early-stage decision-making in reducing embodied carbon, highlighting the need for robust methodologies and interdisciplinary collaboration (Crawford and Stephan, 2020).

3.4.1.4 Construction industry

The construction industry's role centres on the practical implementation of carbon reduction measures. Site practices, material selection, and waste management directly impact embodied carbon emissions. Contractors can achieve significant annual reductions in construction-phase emissions through improved practices. The International Finance Corporation report titled "Building Green: Sustainable Construction in Emerging Markets" indicates that adopting green construction practices could reduce global carbon emissions in construction value chains by around 23% by 2035, equating to an annual average reduction of 1.5% (International Finance Corporation, 2023).

Challenges: Achieving deeper reductions requires fundamental changes to construction methods and supply chain management.

Strategies: Contractors should adopt lean construction practices, prioritize low-carbon materials, and work closely with designers and suppliers to optimize carbon outcomes.

Giesekam et al. explore the challenges of implementing low-carbon strategies in construction, emphasizing the need for improved collaboration and innovation in construction practices (Giesekam et al., 2016).

3.4.1.5 Material manufacturers and supplier

Materials manufacturers and suppliers form a crucial link in enabling carbon reduction through product innovation and transparency. The UKGBC Roadmap identifies ambitious targets for manufacturers, including complete decarbonization of cement production and a 46% reduction in steel emissions by 2050 (UK Green Building Council, 2021).

Challenges: These transformations require significant investment and technological advancement, highlighting the need for supportive policy frameworks and market demand.

Strategies: Manufacturers should invest in low-carbon technologies, provide product-specific Environmental Product Declarations (EPDs), and collaborate with designers to develop innovative solutions.

Passer et al. highlight the importance of EPDs in providing reliable data for embodied carbon assessments, underscoring the critical role of material manufacturers in supporting WBLCA (Passer et al., 2015).

3.4.1.6 Building operators and users

Building operators and users represent the final link in the stakeholder chain, controlling operational performance and enabling verification of design intentions. Their ability to monitor, report, and optimize building performance is essential for closing the performance gap between design and actual carbon emissions.

Challenges: Operational inefficiencies often arise from a lack of post-occupancy evaluation and continuous performance optimization.

Strategies: Operators should implement robust monitoring systems, conduct post-occupancy evaluations, and engage users in energy-saving practices.

Moncaster et al. emphasise the importance of operational performance in achieving carbon reduction targets, highlighting the need for continuous monitoring and optimization (Moncaster et al., 2019).

3.4.1.7 Educators

Educators play a vital role in equipping the next-generation of construction professionals with the knowledge and skills needed to implement WBLCA effectively. Universities and training institutions are increasingly integrating embodied carbon assessment into their curricula, ensuring that graduates are prepared to address the challenges of sustainable construction.

Strategies for Educators:

- Curriculum Development: Incorporate WBLCA methodologies and tools into architecture, engineering, and construction management programs.
- Interdisciplinary Training: Promote interdisciplinary learning opportunities that encourage collaboration between students from different disciplines.
- Industry Partnerships: Partner with professional bodies and industry leaders to provide students with practical experience in carbon assessment and reduction.
  Adams et al. stress the importance of education in addressing the skills gap in sustainable construction, emphasizing the need for interdisciplinary training to prepare professionals for the complexities of embodied carbon reduction (Adams et al., 2018).

3.4.1.8 Interdependencies and barriers to collaboration

Analysis reveals several critical dependencies between stakeholder groups. Early collaboration between clients, designers, and contractors is particularly important for optimizing carbon outcomes. Similarly, integration between designers and manufacturers enables innovation in low-carbon materials and systems. However, traditional industry structures and procurement methods often inhibit such collaboration.

Barriers: Fragmented responsibilities, misaligned incentives, and varying levels of carbon literacy across stakeholder groups hinder effective coordination.

Strategies: Addressing these barriers requires structural changes to industry practices, targeted capacity-building initiatives, and the development of shared metrics, knowledge platforms, and verification protocols.

Pomponi and Moncaster highlight the importance of multi-stakeholder collaboration in achieving sustainable construction practices, emphasizing the need for shared responsibility and continuous dialogue (De Wolf et al., 2017).

Achieving whole life carbon reductions requires synchronised action across the stakeholder ecosystem. Success depends not only on individual stakeholder capabilities but also on the strength of relationships and alignment of incentives between different actors.

4 Discussion

4.1 Assessment systems' effectiveness and limitations

This review aims to provide a critical synthesis of existing research on Green Building Rating Systems (GBRS) and Whole Building Life Cycle Assessment (WBLCA), highlighting their strengths, limitations, and potential for integration. The work seeks to analyse and contextualise these findings within the specific context of the United Kingdom construction sector and its climate targets. By comparing GBRS and WBLCA, identifying gaps in current methodologies, and exploring the role of emerging technologies like BIM, IoT, and digital twins, this review offers a comprehensive framework for advancing sustainable building assessment practices.

One key contribution of this review is its systematic analysis of how GBRS and WBLCA align with the United Kingdom's net-zero emissions target by 2050. While previous studies have examined these assessment methods individually, this paper provides a comparative analysis that highlights their complementary strengths and weaknesses. For example, GBRS are effective at driving improvements in operational energy efficiency and indoor environmental quality, but they often overlook embodied carbon and lifecycle impacts. In contrast, WBLCA offers a more quantitative approach to assessing environmental impacts and has the potential to become more holistic in the future, particularly if aligned with frameworks such as planetary boundaries. However, it is not yet fully holistic, as it currently faces significant challenges related to data quality, methodological complexity, and practical implementation. These limitations hinder its ability to comprehensively address all aspects of environmental sustainability at this stage.

Another contribution of this review is its exploration of how emerging technologies can address the limitations of traditional assessment methods. While the potential of BIM, IoT, and digital twins has been discussed in the literature, this paper critically evaluates their current applications and future potential in the context of WBLCA. For instance, while BIM-integrated WBLCA can streamline data collection and improve assessment accuracy, its effectiveness is limited by data interoperability issues and the dynamic nature of construction processes. Similarly, IoT and digital twins offer opportunities for real-time monitoring and continuous optimization, but their use is constrained by data reliability and feedback loop challenges.

As buildings become more energy-efficient in their operational phase, embodied carbon—the carbon emissions associated with material production, construction, and end-of-life processes—represents an increasingly significant portion of a building's total lifecycle emissions. Studies such as Röck et al. have shown that embodied carbon can account for up to 50% of a building's total carbon footprint over its lifecycle, particularly in low-energy or net-zero energy buildings (Röck et al., 2020). This shift in the relative importance of embodied carbon underscores the need for assessment methods that address both operational and embodied impacts to achieve comprehensive sustainability goals.

4.2 Progress and challenges in implementation

The construction industry has made substantial progress in standardising assessment approaches through initiatives such as the RICS Professional Statement on whole-life carbon assessment and the development of Environmental Product Declarations (EPDs). For example, the RICS Professional Statement, published in 2017, provides a framework for consistent whole-life carbon assessment practices, which has been widely adopted in the United Kingdom and beyond (Royal Institute of Chartered Surveyors, 2024). Similarly, the growth of EPDs, which provide verified data on the environmental impacts of construction materials, has enabled more accurate and transparent assessments of embodied carbon. These initiatives have laid the foundation for more consistent and reliable assessment practices, though challenges remain in addressing complex building systems and renovation projects (Soust-Verdaguer et al., 2022).

Data quality and availability emerge as persistent challenges in implementing WBLCA effectively. While the development of standardised lifecycle inventory data has progressed significantly through initiatives like the EcoInvent database's alignment with EN 15804, gaps remain in regional coverage and specific building components. This established framework provides a foundation for environmental product declarations, though continued work is needed to expand data coverage and improve accuracy for various construction elements.

The construction industry's understanding of embodied carbon and its calculation has evolved significantly over time, driven by advancements in research, methodology, and industry guidance. A key example of this evolution is the development of the Institution of Structural Engineers (IStructE) guidance documents, *How to Calculate Embodied Carbon* (The Institution of Structural Engineers, 2011).

The first edition, published in August 2020, established a foundational methodology for assessing embodied carbon in structural materials. It focused on standardizing calculations and introduced principles for estimating carbon impacts across different structural elements. However, it provided limited detail on certain lifecycle stages and material-specific considerations (The Institute of Structural Engineers, 2020).

The second edition, released in April 2022, expanded on this foundation by refining methodologies, improving clarity on material-specific emissions, and addressing a wider range of lifecycle stages beyond material production. It also placed greater emphasis on data transparency and the use of Environmental Product Declarations (EPDs) (Gibbons, 2022).

The third edition, published in January 2025, represents a significant advancement in embodied carbon calculation. It incorporates the latest research on carbon sequestration in timber, updated benchmarks for low-carbon concrete technologies, and improved guidance on system boundaries, uncertainty analysis, and scenario modelling. This edition further aligns with international standards, providing practitioners with a more comprehensive and robust framework for assessing embodied carbon (The Institution of Structural Engineers, 2024).

The evolution of the IStructE guidance documents reflects the growing sophistication of embodied carbon calculation methodologies and the industry's increasing focus on reducing carbon emissions across the building lifecycle.

The integration of advanced technologies with assessment methodologies demonstrates significant potential for addressing current limitations. Building Information Modelling enables automated data extraction and real-time performance monitoring, potentially reducing resource requirements for conducting assessments. However, the effectiveness of these technological solutions depends heavily on industry-wide adoption and standardisation of data collection protocols.

Machine learning and artificial intelligence applications offer promising solutions for managing assessment complexity. These technologies could enhance the accuracy of environmental impact predictions and enable more dynamic performance evaluation. However, their implementation requires careful consideration of data quality requirements and the need for transparency in decision-making processes. The balance between technological capability and practical applicability remains a critical consideration for future development.

4.3 Regional adaptation considerations

The application of building assessment systems across different regulatory environments presents distinct challenges, particularly in regions with varying climate conditions, construction practices, and market maturity. Analysis by Mulya et al. demonstrates how local context significantly influences assessment system effectiveness, with their study of high-rise buildings in Malaysia revealing how tropical climate conditions fundamentally affect building performance priorities (Mulya et al., 2024). Their findings show cooling systems accounting for approximately half of building energy consumption in tropical regions, contrasting markedly with temperate climate requirements.

The comparison between international and local assessment systems provides valuable insights into adaptation challenges. While LEED achieves higher overall carbon reductions in the Malaysian context (up to 61.1% for LEED Platinum *versus* 28.7% for GreenRE Platinum), local systems like GreenRE show better alignment with regional construction practices and material availability (Mulya et al., 2024). This aligns with findings from Awadh, who identified significant variations in how international rating systems perform across different geographical contexts (Awadh, 2017).

The implementation of Whole Building Life Cycle Assessment (WBLCA) in developing countries presents specific challenges regarding data availability and material certification. Mulya et al. document how their Malaysian case study required materials to be sourced internationally due to limited local Environmental Product Declaration (EPD) availability (Mulya et al., 2024). For example, green cement was imported from New South Wales, Australia, contributing to 50.2% of the material's embodied carbon. This demonstrates how material sourcing decisions in regions with limited local EPD availability affect overall environmental impact.

Technical implementation faces distinct regional challenges. The study's analysis of radiant cooling slabs demonstrates that while this technology reduced cooling energy by 99%, it required additional mechanical ventilation at 1.25 × 106 kW h/yr due to the building's height and uneven air distribution challenges. This exemplifies how technical solutions require careful evaluation within local contexts.

Market conditions particularly influence assessment system adaptation. The study by Doan et al. comparing LOTUS, LEED, and Green Mark systems found that successful adaptation requires careful consideration of local market readiness and technical capabilities (Doan et al., 2017). This is evidenced in the Mulya et al. analysis, where GreenRE's certification criteria were adapted to local conditions with less stringent ecolabelling requirements compared to LEED (Mulya et al., 2024).

Climate-specific considerations significantly impact assessment system effectiveness. In tropical regions, Thomas and Abraham identified the need for specialized assessment criteria addressing unique environmental challenges (Thomas and Abraham, 2020). The Mulya et al. findings support this, demonstrating how cooling load management and façade thermal performance become critical factors in tropical high-rise buildings (Mulya et al., 2024).

The experience of tropical regions offers valuable insights for other jurisdictions adapting building assessment frameworks. The findings demonstrate how assessment methodologies may need modification to account for local material availability, technical constraints, and market conditions while maintaining environmental assessment rigor. Future research could usefully examine how these adaptations affect long-term environmental performance across different regional contexts.

4.4 Future directions and industry implications

The United Kingdom context provides valuable insights into the evolution of building assessment systems. The country's invention of BREEAM and subsequent development of assessment approaches, combined with its legally binding climate targets, creates both imperative and opportunity for advancing assessment methodologies. The experience of implementing various assessment approaches in the United Kingdom market offers important lessons for other jurisdictions pursuing similar environmental objectives.

Green Building Rating Systems (GBRS), such as BREEAM, LEED, and Green Star, have played a significant role in improving building sustainability by establishing standardised frameworks for assessing and certifying environmental performance. These systems have driven improvements across multiple sustainability criteria, including energy efficiency, water conservation, material selection, and indoor environmental quality. For example, studies have shown that BREEAM-certified buildings achieve 25%–30% reductions in energy use compared to non-certified buildings, primarily through the adoption of energy-efficient technologies and renewable energy systems (BREEAM Impact Studies, 2024). Similarly, LEED-certified buildings have been found to use 20%–30% less water than conventional buildings, thanks to the implementation of water-efficient fixtures and rainwater harvesting systems (U.S. Green Building Council, 2018).

GBRS have also encouraged the use of sustainable materials by awarding credits for materials with low environmental impacts, such as those with Environmental Product Declarations (EPDs) or third-party certifications (e.g., FSC-certified timber). This has led to increased demand for sustainable materials and greater transparency in the supply chain (Berardi, 2012). In addition to environmental benefits, GBRS have contributed to improvements in indoor environmental quality, which has been linked to enhanced occupant health and productivity. For instance, BREEAM-certified buildings are required to meet strict criteria for ventilation, thermal comfort, and daylighting, resulting in healthier and more comfortable indoor environments (Newsham et al., 2009).

Looking forward, the evolution of building assessment systems must balance comprehensive environmental evaluation with practical implementation considerations. This requires careful attention to industry capacity, data availability, and the regulatory framework supporting assessment requirements. The development of more integrated approaches, combining the accessibility of rating systems with the rigor of lifecycle assessment, represents a promising direction for future development.

These findings have significant implications for policy development and industry practice. They suggest the need for a more coordinated approach to building assessment, potentially incorporating elements of both rating systems and lifecycle assessment methodologies. This could involve developing hybrid frameworks that maintain the market engagement benefits of rating systems while incorporating the quantitative rigor of lifecycle assessment.

Professional development and industry education emerge as critical factors in advancing assessment practices. The successful implementation of more sophisticated methodologies requires enhanced technical capabilities across the construction sector. Investment in training and tools to support these approaches will be essential for their effective adoption and use in practice.

The analysis indicates that while current assessment systems have contributed to improving building sustainability, significant evolution is needed to meet the challenges of achieving climate targets.

The future of building assessment lies in developing more dynamic, data-driven approaches that can effectively capture and evaluate environmental impacts throughout the building lifecycle. Current systems, such as Green Building Rating Systems (GBRS), have proven inadequate in addressing emerging challenges like embodied carbon and lifecycle performance, as highlighted by Pomponi and Moncaster (Pomponi and Moncaster, 2016).

In contrast, emerging approaches like Whole Building Life Cycle Assessment (WBLCA) and BIM-integrated assessments offer the potential for more continuous and adaptive evaluation of environmental impacts. For instance, Soust-Verdaguer et al. demonstrate how BIM-integrated WBLCA can streamline data collection and improve assessment accuracy, enabling real-time optimization of building performance (Soust-Verdaguer et al., 2017). Similarly, the integration of IoT (Internet of Things) and machine learning technologies, as discussed by Gubbi et al., provides opportunities for real-time monitoring and predictive modelling, which can enhance the responsiveness and accuracy of building assessments (Gubbi et al., 2013).

However, the transition to more dynamic assessment methods requires addressing challenges such as data quality, interoperability, and methodological complexity. For example, Marsh et al. highlight the need for standardised data protocols and uncertainty analysis to ensure the reliability of dynamic assessment approaches (Marsh et al., 2023). By overcoming these challenges, the construction industry can develop more effective tools for achieving sustainability goals and aligning with evolving climate targets.

5 Conclusion

This study has examined sustainable building assessment systems, focusing on the comparative analysis of Green Building Rating Systems (GBRS) and Whole Building Life Cycle Assessment (WBLCA) within the United Kingdom construction sector.

While Whole Building Life Cycle Assessment (WBLCA) offers a more comprehensive and data-driven approach to assessing environmental impacts compared to Green Building Rating Systems (GBRS), it is important to clarify what this means in practice. WBLCA is considered more comprehensive because it evaluates a building's environmental performance across its entire lifecycle, from material extraction and construction to operation and end-of-life, whereas GBRS typically focus on operational performance and specific sustainability criteria (e.g., energy efficiency, water use). For example, WBLCA can quantify embodied carbon, which is often overlooked in GBRS frameworks, as demonstrated by Pomponi and Moncaster (Pomponi and Moncaster, 2016).

WBLCA is also considered more data-driven because it relies on quantitative data and scientific methodologies to assess environmental impacts, such as life cycle inventory (LCI) data and Environmental Product Declarations (EPDs). This allows for more precise and transparent evaluations of a building's carbon footprint, resource use, and other environmental impacts. For instance, Soust-Verdaguer et al. highlight how BIM-integrated WBLCA can automate data collection and improve assessment accuracy, enabling more informed decision-making (Soust-Verdaguer et al., 2017).

However, the comprehensiveness and data-driven nature of WBLCA come with challenges, such as the need for high-quality data, methodological consistency, and significant resources to conduct assessments. While GBRS like BREEAM and LEED have been widely adopted and have a proven track record of driving improvements in energy efficiency, water conservation, and indoor environmental quality, WBLCA is still in the early stages of adoption and requires further development to achieve its full potential.

Three critical priorities emerge from this study: the development of dynamic assessment approaches capable of evaluating lifecycle building performance, the integration of embodied carbon assessment into mainstream practice, and the creation of assessment tools that balance technical capability with practical usability. The findings emphasize the importance of professional development and industry education in advancing assessment practices, supported by sustained investment in training and tool development.

The United Kingdom's experience in implementing building assessment systems offers valuable insights for the global construction industry. While the construction industry is making progress toward environmental targets such as net-zero emissions, it is important to recognize that these targets represent the bare minimum required to mitigate the worst impacts of climate change. True ambition would go well beyond net zero, aiming for regenerative design and carbon-negative outcomes that actively restore ecosystems and reverse environmental damage (Mang and Reed, 2012).

However, achieving even the current targets requires significant transformation in building design, construction, and operation. For instance, the United Kingdom's Climate Change Act sets legally binding carbon budgets and emissions reduction targets, which have driven improvements in energy efficiency and renewable energy adoption. Yet, as highlighted by Pomponi and Moncaster, the construction sector must also address embodied carbon, and lifecycle impacts to meet these targets effectively (Pomponi and Moncaster, 2016).

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Conflict of interest

Author SF was employed by Mace.

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Generative AI statement

The authors declare that Gen AI was used in the creation of this manuscript. To proofread the manuscript. Some references were cross checked and formatted using generative AI.

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