SASBE 2025 aims to encourage the international exchange of innovative ideas between researchers from academia and industry. In addition to knowledge dissemination, the conference offers a valuable platform for professional networking, particularly benefiting university professors, graduate students, and postdoctoral researchers.

Research Article

Embodied Management Drivers (EMDs) as Catalysts for Smart Sustainability in the Built Environment

Harshi Bamunuachchige[1] Min An[2]

Affiliation 1 University of Salford, United Kingdom
Affiliation 2 University of Salford, United Kingdom
H.M.Bamunuachchige@edu.salford.ac.uk
Correspondence: e-mail@e-mail.com

Abstract

Purpose: The UK Construction sector faces urgent challenges in reducing greenhouse gas emissions to meet the national Net Zero Targets by 2050.Curretly, construction activities contribute approximately 39% of UK total carbon emissions, with embodied carbon forming the majority share. This study aims to identify and evaluate critical Embodied Carbon Management Drivers (EMDs) that can enhance sustainability in smart building construction, with a focus on early design stage and planning.

Design/methodology/approach: A Comprehensive systematic literature review was conducted, analyzing selected peer reviewed and industry sources to identify potential EMDs.Extracted data was categorized into environmental, economic and social factors. The analysis focused on identifying gaps in practical situation of EMDs during early design and planning stages of construction projects.

Findings: Thirteen key EMDs were identified: environmental (6), economic (3) and Social (4). These include low carbon design strategies, adoption of ecofriendly materials, targeting higher EPC ratings, minimizing maintenance needs, integrating social responsibility among stakeholders and applying recognized best practices. The findings emphasise that early co-operation EMDs can significantly reduce embodied carbon and accelerate the sector's shift toward a low carbon culture.

Originality/value: The study is based on literature derived data, which may not capture all real-world variables in project execution. Future research could validate these findings through empirical case studies and pilot projects.

Keywords: Embodied Carbon Emissions, Greenhouse Gas Emissions, Net Zero Targets, Low Carbon.

Highlights

- Identifies crucial embodied carbon drivers for intelligent sustainable structures in the UK.
- Discloses deficiencies in the implementation of EMDs during the initial design and planning phases
- Advocates for the implementation of EMD to expedite Net Zero Objectives in Construction.

1 Section 1- Introduction

The Architecture 2030 (2023) stresses the fact that the obligation of the built environment sector is to mitigate carbon emissions; hence, the current built environment sector is responsible for 42% carbon emissions annually. In addition, UKGBC's (2021) Net Zero Whole Life Carbon Roadmap displays that the built environment sector is accountable for 25% of UK emissions. Carbon emissions generated through construction activities bring a huge burden to the earth, hence high-carbon-impact materials are cement, steel, iron, and aluminium, which represent 15%of annual global carbon emissions. However, no equivalent regulation currently exists for embodied carbon emissions. Given the UK's commitment to achieving net zero by 2050, updating legislation and policy frameworks is essential to close this regulatory gap and ensure meaningful progress. Gillespie and McIlwaine (2021) highlighted that the UK construction industry faces significant challenges in managing embodied carbon. Therefore, to mitigate this pressing issue, the aim of this research is to identify the drivers of embodied carbon management to improve the environmental management performance in the built environment sector. The study highlights a significant gap in the underutilisation of Embodied Carbon Management Drivers (EMDs), which include embodied carbon management regulations, sustainable rating systems, and environmental management strategies. These mechanisms are vital for achieving sustainable targets in the UK built environment but are often overlooked or poorly implemented during the early design and planning stages for smart building projects. This limited application rejects their potential to drive systematic efficiency and smart sustainability. By establishing key EMDs as key enablers and smart embodied carbon management drivers, this research aims to address the gap and support the UK transition towards a low-carbon future.

2 Importance of Embodied Carbon (EC) Management

The construction sector is at a critical point in its pursuit of sustainability, with a greater emphasis on reducing embodied carbon. Embodied carbon, which includes all greenhouse gas emissions associated with the production, transportation, installation, maintenance, and disposal of building materials, is a substantial component of a building's total carbon footprint. Anyhow, the focus of research has constantly been on operational emissions; however, attention is gradually transitioning to embodied carbon because of its enduring environmental consequences. Therefore, to decarbonise building projects, it is essential to maintain effective communication with construction product and material manufacturers.

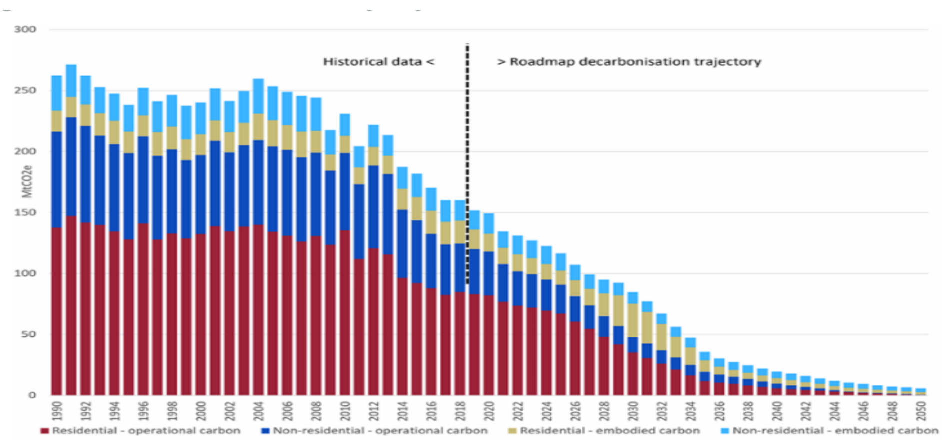

Figure 1: Historical and predicted trajectory of Carbon Emissions (UKGBC,2021)

Figure 1: Historical and predicted trajectory of Carbon Emissions (UKGBC,2021) indicates historical and predicted trajectory of carbon emissions in the UK Sector, differentiating between operational and embodied emissions in residential and non-residential buildings (UKGBC,2021). The data indicate that operational emissions have persistently surpassed embodied emissions, with residential structures representing the predominant portion. Since 2010,Operational emissions have significantly decreased, mostly due to improved energy efficiency standards, the decarbonisation of the power system, and the adoption of low-carbon technology (CCC,2019;).Conversely, embodied emissions-stemming from material production,transportation,construction, and demolition -have remained relatively constant, indicative of the carbon-intensive characteristics of traditional construction materials and the slow adoption of low-carbon substitutes (Gieskam et al.,2015;Pomponi and Moncaster ,2017). This discrepancy underscores the varying effects of policy interventions, where operational performance is infringed upon by more regulatory frameworks, whereas embodied carbon has been largely overlooked in UK Climate Policy (CCC,2020). According to the RICS Sustainability Report (2023), the UK's Overall score for climate action is insufficient. This indicates that current policies and measures are insufficient to achieve the reduction

required to keep global warming below 1.5 °Celsius. The report also emphasizes the notable gaps, particularly in fair share contributions and climate finance.

2.1 Embodied Carbon (EC) and EMDs

Embodied carbon refers to greenhouse gas emissions associated with the material extraction, manufacturing, transportation, assembly, maintenance, and end-of-life disposal of building materials over their full life cycle (RICS, 2017). Embodied carbon is an urgent climate priority to prevent irreversible and catastrophic climate change; the Paris Agreement stipulates that the rise in average global temperatures must be limited to more than 2 °C. The most critical challenge with embodied carbon is that it is released during the production or initial stages of building construction, which are often overlooked at the earliest stages. Therefore, if a proper decision is not made at an early design stage, it is impossible to remove the upfront embodied carbon later, making early intervention to reduce embodied carbon critical. Manufacturing, transportation, assembly, maintenance, and end of life disposals of building materials over their full life cycle (RICS,2017). Embodied carbon is an urgent climate priority to prevent irreversible and catastrophic climate change; the Paris agreement stipulates that the rise in average global temperatures must be limited to more than 2 °C. The most critical challenge behind embodied carbon is it is released in the production stage or initial stage of building constriction which is ignored at earliest. Therefore, if early design stage proper decision is not made it is impossible to remove the upfront carbon later which makes early intervention to reduce embodied carbon is critical.

Table 1-Phases and Types of Embodied Carbon

Phase	Description	Key Source
Upfront embodied Carbon	Emissions resulting from the extraction of raw materials, manufacturing process, transportation and construction prior to building utilisation.	(Pomponi and Moncaster,2016, Cabeza et.al.,2014)
In Use embodied Carbon	Emissions resulting from maintenance, repair, replacement and refurbishment during the usage phase.	(Dixit,2017)
End of Life embodied Carbon	Emission resulting from demolition, waste processing, transportation and disposal, Possibility for circular reutilisation.	(Zhang e.al 2019)
Avoided/Sequestered Carbon	Biogenic Carbon storage renewable, bio-based materials	(Penloza et.al.,2016)

The HM government UK (2013) launched the Construction 2025 Plan, which stipulates guidelines aiming to reduce carbon emissions and promote the use of sustainable materials such as sustainable timber, low-carbon concrete, and recycled steel. In addition, these guidelines provide directives towards regulatory and policy frameworks, innovative construction practices, circular economy practices, and transparency in reporting carbon emissions. Nevertheless, it appears that the construction sector is implementing these restrictions at a slow pace, and there is no proof that they are effectively reducing embodied carbon emissions. Gilliot et al., (2025) Build zero report analysis indicates six key insights to reduce embodied carbon emissions in the UK built environment sector, such as significant disparity in emission distribution, limited impact of local policies alone, potential for emission reduction via regulation, importance of national approach, variation in building types and policy risks, and conservative modelling assumptions.

1. Significant disparity in emission distribution-embodied carbon emissions are disproportionately distributed across the local planning authorities. This underscores the strategic significance of prioritising interventions in these high-impact areas to optimise carbon reduction results.

2. Limited impact of local policies alone: Although municipal rules provide important examples, their current scope affects only about 1% of embodied carbon emissions. This highlights the necessity of national policy to facilitate significant and scalable decarbonisation within the built environment.

3. Potential for emission reduction via regulation: National regulatory restrictions, based on current local policies, might decrease embodied emissions by as much as 31%, while more ambitious frameworks, such as France's RE2020, may provide reductions of up to 59%. These findings illustrate the significant mitigating potential of strong, well-structured national legislation.

4. The importance of a national approach lies in the dispersed nature of emissions and the variety of building types across regions, which render exclusive dependence on local initiatives prone to fragmentation and inefficiency. A cohesive national policy is crucial for ensuring uniform advancement towards climate objectives and fair execution.

5. Variation in building types and policy risks: Diversity of building types among local planning authorities creates hazards of inconsistent policy effects and regulatory compliance. Uniform national standards can alleviate these issues by fostering consistency, equity, and efficient compliance.

6. Conservative modelling assumptions: This analysis employs conservative assumptions about market dynamics and regulatory acceptance, suggesting that real emissions reductions may exceed forecasts if industry adaptation accelerates. This conservative foundation strengthens the argument for assertive policy measures and proactive stakeholder involvement.

These insights collectively stress the necessity of implementing coordinated, nationwide rules on embodied carbon to effectively achieve climate mitigation objectives. The implementation of conventional buildings has generated controversy among stakeholders due to the several benefits of constructing high-performance buildings, such as ease of construction, the use of readily available and accessible materials, lower initial costs, and fewer technological issues. The Royal Institute of British Architects (2020) report on "Principles of Low Carbon Design and Refurbishment" highlighted the fact that, in the 20th century, architects faced a new challenge: creating low-carbon structures that emit less carbon than conventional buildings. However, Ghansah et al. (2021) debated the challenge of implementing sustainable design in buildings, owing to aspects such as procuring sustainable materials and equipment, difficulties in understanding sustainability standards in contract specifications, and efforts to engage stakeholders in adopting new construction methods. For instance, a typical multi-storey building erected using traditional methods and materials such as cement bricks for the façade, concrete, steel, spray foam insulation, tiles, and carpets results in a significant carbon footprint and environmental impact.

Table 2. EMDs in Sustainable Building Construction

EMD'S	Description
Low Carbon Design (LCD)	Low-carbon design is the most vital factor to consider in the initial stage of smart building construction through energy efficiency, renewable integration and reduced embodied carbon Rasmussen, Birkved, and Biagiotti (2020).
Eco Friedly Materials (EM)	Initiate the need for the use of recycled materials rather than the use of fresh materials since it minimises the landfill and offers lower embodied carbon emissions compared to fresh materials (Eberhardt, Birkved and Birgisdottir, 2020). Knapic et al., (2016) emphasized that the use of cork as an eco-friendly material provides several benefits, including high R-value (thermal comfort), acoustic insulation, durability, and ecological impact.
Design for Durability (DD)	Design for durability means utilising enduring, resilient materials to prolong their longevity. Durable structures diminish the

	necessity for regular renovations or reconstruction and thereby reduce the embodied carbon over time.
Design for Recyclability (DR)	Design for recyclability entails the deliberate incorporation of building materials and structural elements during initial design phase to enable subsequent deconstruction, reuse and recycling of building components and materials (Andrade and Braganca 2019). This method directly tackles the significant environmental consequences of construction and demolition waste by advocating for circular economy in the built environment (Wang et al.,2021).
Ecological Construction (EC)	Ecological construction methods contribute to a significant and comprehensive approach to the construction of buildings, enhancing the calibre for evaluating environmental performance.
Smart Gardening (SG)	Smart gardening in UK building construction is progressively incorporated into architectural designs, utilising novel technology to improve sustainability and urban life. This methodology includes many methods such as vertical greening and intelligent indoor horticulture, which collectively seek to enhance environmental quality and foster biodiversity in urban environments.
Best Construction Practices (BCP)	Use of sustainable construction methods and practices provides waste management strategies, reduce the carbon impact and energy efficient strategies
Carbon Offsetting (CO)	Carbon offsetting is a critical mechanism for reimbursing greenhouse gas emissions produced during construction and operation by investing in initiatives that mitigate or eliminate an equivalent quantity of carbon from the atmosphere.
Social Responsibility (SR)	The concept of social responsibility in construction generally involves ensuring that projects are environmentally sustainable, socially equitable and economically viable. It is the duty of the built environment sector in construction to integrate social responsibility, moving beyond mere compliance to foster positive societal impacts (Jiang and Wong,2015)
Regulatory Compliance (RC)	Despite the escalating urgency of climate change, numerous construction firms and stakeholders persist in neglecting embodied carbon. The lack of explicit and enforceable rules addressing embodied emissions is one cause, in contrast to operational energy, which is governed by more stringent building codes and standards (Pomponi and Moncaster,2017).
High EPC (HEPC)	Obtaining high energy performance certificate reflect the stakeholders' best practices to achieve net zero goals and it provides high market value and reduce the environmental impact
Low Energy Bill (LEB)	This focus on use of energy efficient technologies and designs that increase operational energy usage, resulting in enduring financial savings.

Low Maintenance Cost (LMC)	Low maintenance cost could achieve through robust design, modern method of construction which reduce repair and maintenance cost through building life span.

2.2 Existing Theories and Frameworks of Embodied carbon (EC)

The measurement and mitigation of embodied carbon in construction are essential for attaining sustainability objectives. Drivers' theories and frameworks have risen to tackle this topic, concentrating on assessment procedures and reduction strategies. The subsequent sections delineate the principal existing frameworks and theories in this topic.

Table 3. Comparison of existing frameworks in embodied carbon (EC)

Authors /Research tile	Frame works /methods	Strengths	Future Directions
Bamunuachchige and An (2025) Mitigating Embodied Carbon: Carbon Assessment Challenges and Methods in Smart Building Construction in the UK	Explicit Systematic Literature Review Expert Interviews addressing UK smart building construction context	Targets UK specific regulatory and Supply challenges Focus on smart building sector	Develop rigorous carbon management strategies. Advances low carbon material availability Integrate low carbon practices in early project stages.
Tigani et .al (2024) Measuring Embodied carbon in Buildings: A Review	Focuses on need of Use of Life Cycle assessments (LCA) and use of Whole life cycle assessments for measuring EC Benchmarking against industry averages and strategies such as material substitution, design optimisation and construction waste	Comprehensive methodology review and aligns with net zero goals. Measuring embodied carbon is essential for reducing carbon emissions	Develop globally standardised LCA protocols and establish industry wide benchmarks.
Lützkendorf & Balouktsi, (2022) Embodied carbon emissions in buildings: explanations, interpretations, recommendations	Focuses on significance of EC, assessment methods	Highlights knowledge gaps in data regulations	Expand databases and tools; Integrate embodied carbon into building codes and regulations
Hu and Esram (2021) The Status of Embodied Carbon in Building Practice and Research in the United States: A Systematic Investigation	Highlights the need of EC frameworks, need of comprehensive methods, EC tools and regulatory frameworks	Highlights knowledge gaps in regulations	Expand databases and tools; Integrate EC into building codes and regulations
Moayedi et al., (2019) A Systematic Approach to Embodied Carbon Reduction in Buildings	Utilises the ISO14040 framework for assessing embodied carbon emissions and introduces a novel optimisation model to manage carbon emissions	Innovative use of optimisation with LCA.	Apply models in varied contexts; scale the methodology internationally

However, key embodied carbon (EC) reduction strategies include low carbon material selection, design optimisation, and the use of regulatory frameworks (Lützkendorf & Balouktsi, 2022; Moayedi et al., 2019; Hu and Esram, 2021). Lützkendorf & Balouktsi (2022 highlighted that selecting low-carbon materials, recycling, and reusing materials are the key to reducing embodied carbon emissions. In addition, Lützkendorf & Balouktsi (2022) and Moayedi et al. (2019) identified that the use of effective design can reduce material consumption and extend the lifespan of the building elements. Lützkendorf & Balouktsi (2022) and Hu and Esram (2021) further emphasized the importance of regulatory frameworks in influencing stakeholders to evaluate embodied carbon emissions and drive the industry towards more sustainable practices. Anyhow, these frameworks offer a systematic approach for quantifying and mitigating embodied carbon, pushing the industry towards robust methods to address this issue. They also underscore the need for standardisation and the incorporation of embodied carbon factors into current building regulations and practices.

2.3 Knowledge Gaps and Research Opportunities

The management of embodied carbon in smart buildings encounters numerous obstacles and knowledge deficiencies that hinder effective execution. While the construction industry has focused considerable attention on addressing operational carbon, embodied carbon remains a critical blind spot, accounting for 50% of building life cycle emissions. This imbalance underscores the urgent need for comprehensive strategies to integrate embodied carbon considerations into smart building design and management.

Table 4 knowledge gaps in embodied carbon management

CATEGORY	DESCRIPTION	SUPPORTING RESEARCH AND SOURCES
REGULATORY FRAMEWORKS	Lack of embodied carbon targets in most building codes; few countries have enforceable policies	Hu and esram (2021); Lützkendorf & balouktsi, (2022)
LIFECYCLE COVERAGE	End of life, reuse and recycling stages are often omitted from assessments leading to incomplete carbon accounting	Hu and esram (2021); Akbarnezhad & xiao, (2017)
BIOGENIC CARBON ACCOUNTING	Inconsistent methods for handling carbon storage and lack of transparency in lca practices.	Pomponi and moncaster (2016)
PROFESSIONAL EXPERTISE AND AWARENESS	Few professionals are trained to assess embodied carbon, Environment literacy in design is low and in construction teams	Bamunuachchige & an (2025)
OPERATIONAL VS EMBODIED CARBON TRADE OFF	Limited guidance on how to balance operational vs embodied carbon	Lützkendorf & balouktsi, (2022); (akbarnezhad & xiao, 2017)
MATERIAL SUPPLY CHAINS	Limited availability of low carbon alternatives; resistance from industry to adopt novel or unfamiliar products	Bamunuachchige & an (2025)
INTEGRATION IN EARLY DESIGN STAGES	Embodied carbon is rarely considered during concept and design phases	Bamunuachchige & an (2025)
EDUCATION AND TRAINING	Embodied carbon management is rarely applied in academic curriculum and cpd sessions	Pomponi and moncaster (2016)
CARBON MANAGEMENT STRATEGIES	Lack of rigorous carbon management frameworks, monitoring and evaluation during construction and inspection	Bamunuachchige & an (2025)
STANDARDISED DATA AND TOOLS	Absence of harmonised lca databases and consistent methodologies across regions; inaccessible datasets	Hu and esram (2021); akbarnezhad & xiao, (2017)
CONTEXT SPECIFIC STRATEGIES	Research always assumes one size fit all approaches: limited tailoring to geographical, cultural and technological contexts.	Pomponi and moncaster (2016); lützkendorf & balouktsi, (2022)

2.4 Proposed Conceptual Model

The conceptual model has been developed considering the embodied carbon management drivers developed and comparing the existing frameworks and models.

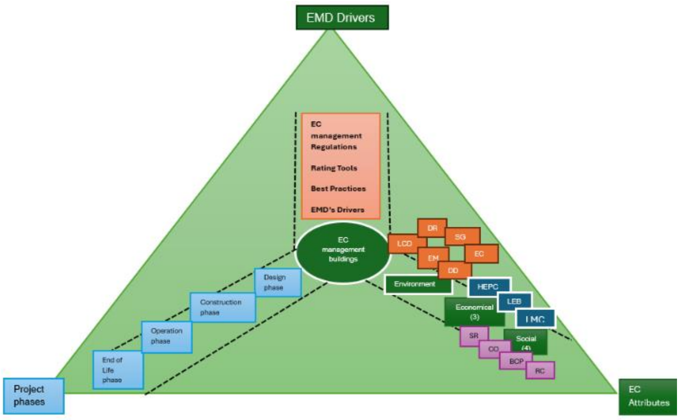

Figure 2. Advanced EC Management Framework

The conceptual model has been developed by integrating the embodied carbon management drives (EMD's) and benchmarking them against existing frameworks and models. This approach ensures that the model not only addresses material selection, design optimisation and process improvements but also aligns with current best practices in carbon assessment, circularity and sustainability. By comparing with established models, the conceptual framework highlight gaps, opportunities, and practical pathways for reducing embodied carbon throughout the construction and design Lifecyle.

The Integration of robust policy frameworks, comprehensive carbon data from sources like Environmental Product Declarations (EPDs) and databases, as well as low carbon and bio-based materials, and circular economy benchmarks, constitutes the foundation for effective embodied carbon management in construction and design. The conceptual model has been formulated by evaluating these embodied carbon management drivers and comparing them with the established frameworks and models. To maximise these inputs, processes must prioritise the standardisation of carbon assessment methodologies, the training of professionals, the integration of assessments throughout all design phases and the implementation of modern method of construction techniques such as prefabrication, reuse, recycle and circular design principles. The expected outcome compromise quantifiable decreases in embodied carbon, improved circularity and sustainability, and conformity with net zero objectives, alongside the identification of essential research domains for ongoing innovation and enhancement in low carbon and circular design methodologies.

3 Methodology

The systematic literature review (SLR)is a methodological research approach that consolidates existing works on a particular subject, offering an exhaustive summary of current understanding and pinpointing areas for further investigation. This method is extensively utilised in fields such as social sciences, healthcare, and management, as it employs a systematic and reproducible approach to data collection and analysis. This study conducted a comprehensive literature review to identify gaps in embodied carbon management in smart buildings, emphasizing essential factors for reducing carbon emissions in the initial phases of smart building design. The review defined explicit parameters utilising terms including "embodied carbon", "environmental impact assessment", "Carbon management methods", "carbon emissions in building construction", and "UK net zero 2050 targets". These keywords were utilised in searches within the Scopus and Web of Science databases, focusing on prestigious journals and conference proceedings to ensure academic integrity. This methodology strengthens the validity of the conclusions by utilising credible, peer-reviewed sources and establishing a firm basis for future research trajectories.

The key components of a systematic literature review are primarily three: research question and formulation, protocol development, and extraction and synthesis. Research Question Formulation: Clearly defining the research question is crucial for guiding the review process (Višić, 2022). Protocol development: establishing a protocol ensures a systematic approach, detailing methods for literature research, screening, and quality assessments (P S et al., 2024). Data extraction and synthesis:

This involves collecting relevant data from selected studies and synthesizing findings to draw meaningful conclusions (Pradana et al., 2023). After conducting a systematic literature review and developing the advanced EC management framework, a case study has been selected to validate the model.

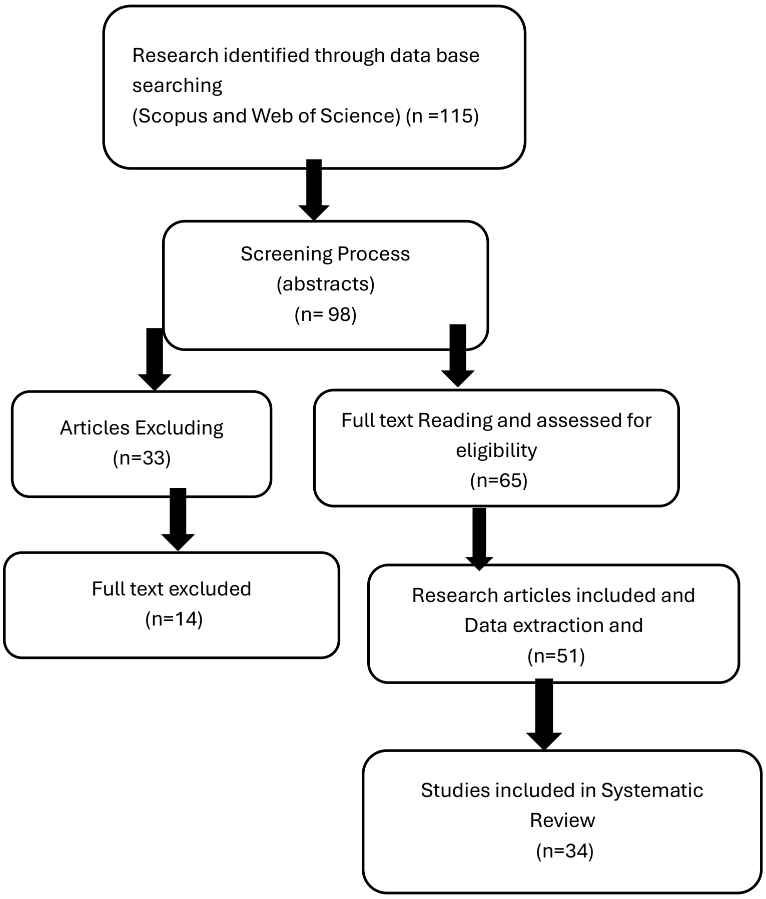

Figure 3. Systemetic Review Process

4 Results- Key Findings

The review article reveals that several key concepts for enhancing embodied carbon control are required in the design and construction stages of building construction. The conceptual model, created by comparing embodied carbon management drivers (EMDs)with established frameworks, illustrates the necessity of synchronising material selection, design optimisation, and process enhancements with best practices in carbon assessment, circularity, and sustainability. The comparative analysis highlights current models' substantial deficiencies, especially regarding the uniformity of carbon accounting systems, the restricted use of circular economy concepts, and the insufficient utilisation of bio-based and low-carbon products. These gaps offer an opportunity for pragmatic solutions through the design and construction lifecycle. The function of the policy and data framework enhances the effective reduction of embodied carbon and necessitates the combination of comprehensive policy frameworks, dependable carbon databases (Ex, EPDs), and transparent reporting systems. Contemporary approaches frequently exhibit a deficiency in standardisation, which obstructs the comparability and scalability of carbon management strategies. Further, results highlight the necessity of integrating carbon evaluations throughout all design stages, allocating resources for professional development, and advocating for contemporary construction techniques (MMC), such as prefabrication, reuse, recycling, and circular design methodologies. Collectively, these methods establish a framework for the systematic reduction of embodied carbon. The conceptual model establishes a robust foundation for embodied carbon management by connecting theoretical principles with practical contexts. It emphasises both the technical and material techniques as well as the policy, data, and procedural enablers crucial for attaining significant decarbonisation in the built environment.

5 Discussion

The research discovered that thirteen fundamental Embodied Management Drivers (EMDs) were classified into environmental (6), economic (3), and social (4) categories. These drivers constitute a comprehensive framework for tackling the sustainability issues related to embodied carbon in the built environment. The environmental EMDs emphasise measures considering the Triple Bottom Line (TBL), such as low carbon design, the use of eco-friendly materials, design for recyclability and durability, ecological construction, and smart gardening. All of these measures directly facilitate the reduction of embodied energy and emissions. Economic rovers prioritise reducing maintenance needs, optimising lifecycle and cost efficiency, advancing sustainability objectives, and improving long-term financial sustainability. Social factors such as stakeholder participation, incorporation of social responsibility, and compliance with established best practices highlight the significance of collaboration and inclusivity in facilitating transformative change.

The findings underscore that the prompt incorporation of EMDs into decision-making processes can serve as a catalyst for intelligent sustainability in the constructed environment. Incorporating these drivers from the outset of project planning and design enables stakeholders to markedly decrease embodied carbon while fostering a culture of low-carbon behaviours. The interaction of environmental, economic, and social factors demonstrates that achieving smart sustainability requires not only technological innovation but also institutional collaboration, cultural transformation, and a commitment to continuous improvement. In this regard, they serve not just as instruments for carbon reduction but also as facilitators of a wider transition towards a low-carbon and socially responsible construction industry.

However, reduction of embodied carbon in structures necessitates a comprehensive strategy that integrates material, design, and policy approaches. Essential measures encompass the adoption of low-carbon materials, the reuse and recycling of components, and the reduction of materials usage through efficient design (Kumari et al.,2019). Local procurement and efficient construction techniques further diminish emissions, while adaptive reuse prolongs building longevity. Policy support and carbon labelling initiatives are crucial for enhancing knowledge and promoting informed decisions, facilitating a transition to a low-carbon and more sustainable building industry.

In comparison to current frameworks and methodologies in the literature, the EMDs framework established in this study offers a more cohesive and management-focused strategy for reducing embodied carbon. Bamunuachchige and An (2025) underscore the importance of systematic reviews and expert interviews to tackle regulatory and supply chain challenges specific to the UK, while Tigani et al (2024) enhance the significance of life cycle assessment and benchmarking strategies. This framework, however, extends beyond these technical methodologies by integrating them into a comprehensive array of environmental, economic, and social management drivers throughout all project phases. Likewise, research by Lutzkendorf and Balouktsi (2022) and Hu and Esram (2021) emphasizes the necessity of enhancing databases and integrating embodied carbon into regulations. While these studies primarily serve a diagnostic purpose, this model translates these practices into applications. Moreover, it involves practical mechanisms such as procurement practices, rating tools, and the adoption of best practices. Moreover, although Moayedi et al (2019) present a novel optimisation model with ISO Frameworks, their research is predominantly methodological, whereas the EMDs framework integrates optimisation as a component of a comprehensive system that also considers stakeholder management, lifecycle cost efficiency, and cultural transformation. The EMDs framework's innovation lies in its ability to integrate technological, regulatory, and social components into a cohesive model. It addresses deficiencies noted in prior research and offers a pragmatic guide to expedite the shift towards smart sustainability in the built environment.

To evaluate the feasibility and real-world relevance of the advanced embodied carbon management framework, it was applied to a real-world building project, hereafter referred to as Building A. The project name and location are withheld to maintain the client's confidentiality. Building A comprises four floors and encompasses 15,500 square meters, significantly reducing environmental impact in various aspects. The Project provides a varied array of advanced facilities for students studying architecture, robotics, computing, physics, aeronautical, civil, electrical, and mechanical engineering.

Table 5 Building A key features.

Element	Description
Size & Structure	Four stories, 15,550 m^2 steel-frame building

Purpose	Provides state-of-the-art facilities for students in architecture, robotics, computing, physics, and engineering (aeronautical, civil, electrical, mechanical)
Key Features	Flight simulators, robotics labs, wind tunnel, Morson Maker Space, triple-height central atrium
Sustainability	Fully electric-powered, BREEAM Excellent-rated, fabric-first approach, mixed-mode ventilation for energy efficiency
Design Highlights	Industrial aesthetic with yellow exposed steel frame, bold red & blue staircases, 45m-long rooflight for natural light
Key Features	Flight simulators, robotics labs, wind tunnel, Morson Maker Space, triple-height central atrium
Sustainability	Fully electric-powered, BREEAM Excellent-rated, fabric-first approach, mixed-mode ventilation for energy efficiency
Construction Cost	£49.3 million (£3,222 per m^2)

Table 6 offers an evaluation of the environmental factors applied to Building A to validate the advanced EC management framework. Six key environmental factors have been incorporated into the project to enhance sustainability and environmental performance. The low-carbon design factor considered strategies to minimize carbon emissions throughout the building lifecycle. Eco-friendly materials factor considered the utilisation of sustainable, nontoxic, and recyclable building materials. Design for durability focuses on long-lasting construction solutions to extend building lifespan and reduce resource consumption. Design for recyclability focuses on using modern construction techniques and facilitating end-of-life material recovery. Application of environmentally conscious construction methods that minimise site disturbance and pollution. Smart gardening highlights the need for green space strategies that support biodiversity and environmental well-being.

Table 6 Environmental Factors Analysis of Building A

Element	Application to case study
Low carbon design (LCD)	Fully electric powered, BREEAM excellent rated, fabric fist approach, mixed mode ventilation has been used.
Eco-friendly materials (EM)	Use of aluminium cladding, sustainable and prefabricated materials, exposed services to reduce waste.
Design for durability (DD)	60-year lifespan, steel frame structure, aluminium cladding,
Design for recyclability (DR)	Prefabricated window reveals, adaptable and modular elements and potential for material use.
Ecological construction (EC)	Sustainable building materials, reduced carbon footprint through efficient construction practices.
Smart gardening (SG)	Limited green infrastructure in design: potential for improvement through green roof or vertical gardens.

The table 7 outlines the evaluation of three economic factors for Building A. Economic factors have been applied and evaluated to understand the nature of the energy performance certificate, low energy bill rating, and low maintenance cost in the building. These factors have been examined to ascertain their influence on the overall building performance. A high energy performance certificate (HEPC) evaluates the building's verified energy efficiency. Low energy billing evaluates the structure’s capacity to sustain a minimised energy cost. Minimal maintenance expenses highlight the enduring cost advantages of resilient materials and effective maintenance practices.

Table 7 Economic Factors Analysis

Element	Application to case study
High epc (HEPC)	Designed for high energy performance, reducing operational carbon footprint.
Low energy bill (LEB)	Fully electric, optimised insulation and energy efficient systems contribute to lower energy costs.
Low maintenance cost (LMC)	Durable materials, prefabricated components and efficient design to reduce long term maintenance costs.

The table 8 delineates the Social Factors analysis, which consists of four social factors: social responsibility, carbon offsetting, best construction practices, and regulatory compliance for Building A. Social responsibility identified the project's dedication to ethical standards and community involvement. A carbon offsetting factor is used to mitigate or compensate for carbon emissions produced by construction operations. The regulatory compliance factor analyses adherence to industry standards, health and safety laws, and sustainable construction applications. 8 Social Factors Analysis.

Table 8 Social Factors Analysis

Element	*Application to case study*
Social Responsibility (SR)	Significant job creation, apprenticeships
Carbon Offsetting (CO)	No direct carbon offset program, but building design minimises operational carbon impact.
Best Construction Practices (BCP)	Incorporation of sustainable methods, prefabrication and collaboration with academic institutions.
Regulatory Compliance (RC)	BREEAM Excellent Rating.

However, according to the research findings, Building A has achieved a BREEAM Excellent rating, demonstrating strong overall sustainability performance. The project confirms a better balance in operational carbon compared to embodied carbon, indicating efficient building operation. Anyhow, several drawbacks were identified, including the absence of living walls or smart gardening techniques and a lack of carbon offsetting strategies. The project relies on standard maintenance routines, which could limit long-term sustainability performance. Therefore, according to Building A analysis, recommendations are made, such as incorporating green infrastructure, use of green walls, design for recyclability and implementation of carbon offsetting strategies. The absence of living walls and smart gardening techniques limits the building's potential for biodiversity enhancement and carbon sequestration. Integrating these elements could contribute to improved air quality and thermal comfort. While the building demonstrates energy efficiency, adopting carbon offsetting initiatives, such as supporting renewable energy projects or reforestation efforts, could mitigate residual carbon emissions. Adoption of carbon-negative materials: utilising materials with lower embodied carbon, such as recycled steel, recycled concrete, or recycled timber, would reduce the impact associated with construction. Enhanced maintenance practices, establishing predictive maintenance routines using digital monitoring tools, could optimise the building's operational efficiency and extend the lifespan of its systems.

6 Conclusions

This study illustrates that embodied management drivers (EMDs) are crucial in influencing trajectories towards intelligent sustainability in the constructed environment. The research categorises thirteen essential EMDs spanning environmental, economic, and social aspects, emphasising the multifaceted character of embodied carbon management. The results highlight that incorporating these factors promptly—namely, low carbon design techniques, sustainable materials, effective maintenance planning, and stakeholder involvement—will contribute to diminishing embodied carbon and expedite the shift towards a low carbon ethos. The consequences surpass carbon reduction, underscoring the importance of systematic coordination, regulatory coherence, and collective accountability among stakeholders. These elements serve as both operational tools for reducing environmental impacts and as accelerators for cultural and organizational change within the construction industry. Subsequent studies ought to expand upon these findings by investigating the operationalisation of EMDs within the digital instruments, policy structures, and performance metrics, thus solidifying their function as essential facilitators for intelligent, sustainable, and resilient built environments. Hence, embodied carbon management via Embodied Management Drivers (EMDs), a series of recommendations can be proposed. From an environmental standpoint, adopting low-carbon and bio-based materials, standardising life cycle assessment (LCA) procedures, and designing for adaptation and durability are crucial for minimising embodied energy and promoting circular economy concepts. Shifting emphasis from initial to lifecycle costs, incentivising carbon-efficient techniques via tax benefits. Further, including embodied carbon concerns in investment decisions can improve both financial viability and sustainability outcomes. Enhanced stakeholder engagement, specialised training initiatives, and comprehensive cultural transformation across sectors are essential for integrating low-carbon priorities into standard practices. At the policy level, obligatory embodied carbon reporting, the establishment of national and global benchmarks, and the implementation of carbon pricing systems would promote accountability. Tools like BIM and AI in the initial design processes, along with experimentation with novel materials and construction techniques, signify crucial avenues for research and innovation. These proposals collectively illustrate that achieving intelligent sustainability requires systematic action across environmental, economic, and social dimensions, supported by policy and technological innovation.

This study has been subjected to various limitations, including a systematic literature review and a focus on selected databases, high-ranking journal papers, and conference papers. Further, this research is limited to the emphasis on embodied carbon management within smart buildings, as well as UK regulatory requirements and industrial reports. Finally, thirteen embodied carbon management drivers were identified and classified within environmental, economic, and social dimensions. Their practical applicability remains unverified through empirical case studies or real-world projects, thereby presenting an opportunity to further research.

Acknowledgements

We genuinely recognize the contribution of the authors whose original papers underpinned our systematic evaluation and also grateful for doctoral school and school of science and engineering for providing the financial support and necessary training to make the journal publication successful.

Funding

This research was funded by the University of Salford. No external funding was received.

Data Availability Statement

The data supporting this research are available from the corresponding author upon reasonable request.

Conflicts of Interest

There is no conflict of interest

References

Architecture 2030 (2023) Why the Building Sector, [online]. Available: https://architecture2030.org/why-the-building-sector , July 15,2025.

Akbarnezhad, A., & Xiao, J. (2017). Estimation and Minimization of Embodied Carbon of Buildings: A Review. *Buildings*, *7*(1), 5. https://doi.org/10.3390/buildings7010005 , July 10, 2025.

Bamunuachchige, H., An, M. (2025). Mitigating Embodied Carbon: Carbon Assessment Challenges and Methods in Smart Building Construction in the UK. In: Dissanayake, R., Mendis, P., De Silva, S., Fernando, S., Attanayake, U., Gajanayake, P. (eds) Proceedings of the 15th International Conference on Sustainable Built Environment. ICSBE 2024 2024. Lecture Notes in Civil Engineering, vol 652. Springer, Singapore. https://doi.org/10.1007/978-981-96-8301-7_20. July18, 2025

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2020). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*, *18*(2), 93–113. https://doi.org/10.1080/17452007.2020.1781588

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G. and Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, pp.394–416. doi: https://doi.org/10.1016/j.rser.2013.08.037 . August 22, 2025

Committee on Climate Change. (2020), Reducing UK emissions:2020 Progress report to Parliament. https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament

Dixit, M.K. (2017). Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. Renewable and Sustainable Energy Reviews, 79, pp.390–413. doi: https://doi.org/10.1016/j.rser.2017.05.051 July 22, 2025

Giesekam, J., Barrett, J. R., & Taylor, P. (2015). Construction sector views on low carbon building materials. Building Research & Information, 44(4), 423–444. https://doi.org/10.1080/09613218.2016.1086872.

Gillespie, D., & McIlwaine, S. (2021). Reducing embodied carbon in the construction sector. Proceedings of the 37th Annual ARCOM Conference, 744–753. Last Access: August 20, 2025

Gillott, Charles; Graham, Miriam; Saxton, Georgie; Giesekam, Jannik; Densley Tingley, Danielle (2025). Projected embodied carbon emissions from England's buildings by location, type and regulatory level. The University of Sheffield. Report. https://doi.org/10.15131/shef.data.29636411.v3, August 22, 2025

Ghansah, F.A., Owusu-Manu, D.-G., Ayarkwa, J., Edwards, D.J., and Hosseini, M.R. (2021). "Exploration of latent barriers inhibiting project management processes in adopting smart building Technologies (SBTs) in the developing countries." Construction Innovation, Vol. 21 No. 4, pp. 685-707.

Jiang, W. and Wong, J. (2015). Embedding Corporate Social Responsibility into the Construction Process: A Preliminary Study. doi:https://doi.org/10.1061/9780784479377.003.

HM Government (2013). Construction 2025: Industrial Strategy -government and industry in partnership. Department of Business, Innovation and Skills. Construction 2025: strategy - GOV.UK .Last access May 25,2025.

Hu, M., & Esram, N. W. (2021). The Status of Embodied Carbon in Building Practice and Research in the United States: A Systematic Investigation. *Sustainability*, *13*(23), 12961. https://doi.org/10.3390/su132312961

Kumari, L. M. T., Madusanka, N., Kulatunga, U., & Jayasena, N. (2019). Embodied Carbon Reduction Strategies for Buildings (pp. 295–308). springer singapore. https://doi.org/10.1007/978-981-13-9749-3_28

Knapic, S., Oliveira, V., Machado, J.S. and Pereira, H. (2016). Cork as a building material: a review. European Journal of Wood and Wood Products, 74(6), pp.775–791. doi:https://doi.org/10.1007/s00107-016-1076-4.

Lützkendorf, T. & Speck, T. (2021) – Combating Greenwashing of Construction Products: A Critical Analysis of Environmental Product Declarations, MDPI Sustainability, 13(15), 8561. Last access June 17,2025.

Moayedi, F., Amila Wan Abdullah Zawawi, N., & Shahir Liew, M. (2019). A Systematic Approach to Embodied Carbon Reduction in Buildings. In *IOP Conference Series: Earth and Environmental Science* (Vol. 220). Institute of Physics Publishing. https://doi.org/10.1088/1755-1315/220/1/012055 Last access June 17,2025.

Peñaloza, D., Erlandsson, M. and Falk, A. (2016). Exploring the climate impact effects of increased use of bio-based materials in buildings. Construction and Building Materials, 125, pp.219–226. doi: https://doi.org/10.1016/j.conbuildmat.2016.08.041. Last access June 16,2025.

Pomponi, F. and Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management*, [online] 181, pp.687–700. doi: https://doi.org/10.1016/j.jenvman.2016.08.036 . Last access June 23,2025.

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. Journal of Cleaner Production, 143, 710–718. Last access June 24.2025.

Višić, M. (2022). Connecting puzzle pieces: Systematic literature review method in the social sciences. Sociologija, 64(4), 543–562. https://doi.org/10.2298/soc22045. Last access June 26,2025.

P S, V., Chakraborty, A., & Kar, A. K. (2024). How to Undertake an Impactful Literature Review: Understanding Review Approaches and Guidelines for High-impact Systematic Literature Reviews. South Asian Journal of Business and Management Cases. https://doi.org/10.1177/22779779241227654 . Last Access: August 12, 2025.

Pradana, M., Silvianita, A., Madiawati, P. N., Calandra, D., & Lanzalonga, F. (2023). A Guidance to Systematic Literature Review to Young Researchers by Telkom University and the University of Turin. To Maega, 6(2), 409. https://doi.org/10.35914/tomaega.v6i2.1915

Rasmussen, F. N., Birkved, M., & Birgisdóttir, H. (2020). Low- carbon design strategies for new residential buildings – lessons from architectural practice. *Architectural Engineering and Design Management*, *16*(5), 374–390. https://doi.org/10.1080/17452007.2020.1747385 Last Access: August 18, 2025.

RICS (2017). RICS Professional statement: Whole life carbon assessment for the built environment. The Royal Institution of Charted Surveyors (RICS). https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the--built-environment-november-2017.pdf. Last Access: August 05, 2025.

Royal Institute of British Architects (2020): Principles of Low Carbon Design and Refurbishment. https://lowcarbonstudio.org/wp-content/uploads/2020/02/RIBA-Principles-of-Low-Carbon-Design-and-Refurbishment.pdf. Last Access: August 15, 2025.

RICS Sustainability Report(2023) [Online] Available at: https://www.rics.org/news-insights/rics-sustainability-report-2023 , (14.6.23) Last Access: August 25, 2025.

Tigani, D., Kan, D., Tennakoon, G. A., Geng, L., & Chan, M. (2024). Measuring Embodied Carbon Buildings: A Review of Methodologies and Benchmarking Towards Net Zero. IOP Conference Series, 1363(1), 012030. https://doi.org/10.1088/1755-1315/1363/1/012030 Last access June 26,2025.

UK Green Building Council (2021). Net Zero Whole Life Carbon Roadmap. [online] UKGBC. Available at: https://ukgbc.org/our-work/topics/whole-life-carbon-roadmap/. Last access June 24,2025.

UK Green Building Council. (2021). *Building the case for net zero: UK built environment whole life carbon roadmap*. https://ukgbc.org/our-work/topics/whole-life-carbon-roadmap/ . Last Access: August 10, 2025.

UK Green Building Council. (2023) Sustainability Essentials Report

Wang, G., Krzywda, D., Kondrashev, S., & Vorona-Slivinskaya, L. (2021). Recycling and Upcycling in the Practice of Waste Management of Construction Giants. *Sustainability*, *13*(2), 640. https://doi.org/10.3390/su13020640

Zhang, X.; Shen, L.; Wu, Y. Green strategy for gaining competitive advantage in housing development: a China study. J. Clean. Prod. 2011, 19, 157–167, https://doi.org/10.1016/j.jclepro.2010.08.005. Last Access: August 12, 2025.

Disclaimer/Publisher's Note