E3S Web of Conferences **546**, 01014 (2024) https://doi.org/10.1051/e3sconf/202454601014
ICoGB 2024

Methodologies for assessing building embodied carbon in a circular economy perspective

Yangxiaoxia Li[1 *[0009-0001-7481-8804]], and *Gabriele* Masera[1[0000-0002-0704-4052]]

[1]Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italy

Abstract. The global warming effect represents an increasingly severe environmental issue in the contemporary world, with the construction industry contributing up to 40% of greenhouse gas emissions. Therefore, as advancements in technology have enabled the realization of net-zero energy buildings, there has recently been a growing focus on research primarily aimed at reducing the embodied carbon (EC) of building materials. Assessment and calculation of EC emissions in buildings typically utilize life cycle assessment (LCA) methodologies, evaluating both direct and indirect carbon emissions throughout all stages, from raw material extraction to end-of-life demolition. However, the substantial potential of carbon reduction within the material beyond life cycle stage in the building, which is the decisive process of closing the loop of circular economy, is often overlooked. This paper examines a large number of research cases on EC in buildings over the past 20 years, selectively identifying those including the benefits beyond life cycle of buildings. By conducting a case-by-case analysis of methods and tools employed for the assessment of circular practices, their respective strengths, weaknesses, and variances are evaluated. Following the normalization of EC in phase A-D, a significant research finding revealing that buildings can offset an average of -113.9 kg CO_{2e}/m^2 of carbon emissions through recycling and reuse in phase D, accounting for 16.85% of the total EC assessed in LCA. Steel recycling offsets the highest amount of carbon emissions, with an average number of -183.86 kg CO_{2e}/m^2. The objective of this paper is to identify the key factors that influence carbon emissions in the circular economy and to identify methods and tools for integrating building materials at the early design stage to minimize EC emissions throughout the entire lifecycle of buildings.

1 Introduction

The global community is currently observing an alarming surge in the quantity, velocity, and magnitude of climate records being shattered: 2023 is projected to establish a new record as the hottest year ever recorded. 1. The IPCC AR6 points out that the globe is 1.1.C (2.F) warmer due to greenhouse gas (GHG) from human activities 2. The International Energy Agency (IEA) released an energy report in 2019, which revealed that carbon emissions from buildings accounted for 39% of the total global carbon emission 3. Among these, 28% were attributed to operational carbon emissions from buildings, while 11% originated from emissions released during the stages of construction materials manufacturing, transportation, construction, maintenance, repair, and end-of-life disposal, known as EC 4. Based on the European Green Deal, it is estimated that material extraction, manufacturing of construction products, and building construction and renovation contribute to approximately 5-12% of total national GHG emissions. Implementing enhanced material efficiency measures has the potential to reduce up to 80% of these emissions. 5. There is a worldwide fast-growing interest on building materials' energy and carbon emissions [6]. Recent studies have emphasized the growing significance of EC as a result of significant efforts aimed at reducing operational carbon emissions 7. When people keep operational carbon at minimum levels, and an increasing number of net-zero energy buildings are realized, it signifies that the EC emissions of buildings have almost become the primary source of carbon emissions from the built environment.

Currently, research on the EC of buildings primarily focuses on the production stage of materials, with few studies addressing the circular recycling and reuse of materials. However, the end-of-life phase of buildings determines whether the materials of a building's lifecycle become a closed loop. Examining the application of building materials from the circular economy perspective would significantly reduce the whole building life cycle carbon. For example, the research shows that the emissions from the production and transportation of all building materials can be almost entirely offset (98% reduction) by the biogenic carbon embodied in timber products if they are reused following deconstruction 8. From the perspective of the circular economy, there is no such thing as waste if all materials can be reused. Therefore, future studies should assess other aspects beyond carbon and energy consumption according to a cradle-to-grave/cradle-to-

* Corresponding author: liyangxiaoxia@outlook.com

cradle system boundary to improve comprehensiveness 9.

This study seeks to conduct a comprehensive analysis of scholarly papers regarding EC in buildings published over the past 20 years. It examines all case studies including building's material LCA of EC in phase D, with 28 out of 266 articles meeting this criterion. The review focuses on methods and tools for calculating building life cycle carbon emissions for material recycling and reuse, as well as the normalization of carbon offset values generated during material recovery. The article systematically collects information and data from both quantitative and qualitative perspectives, placing all cases under the same standard to assess the current status of EC within a circular economy context. Finally, the article discusses the results of the gathered information and data, along with prospects for future research directions.

2 Embodied carbon in the circular economy: State-of-the-art

2.1 Building embodied carbon and circular economy

In the past few years, a wide variety of regulatory tools and a rich normative framework on circular economy have been established. The concept of the circular economy focuses on revolutionizing the complete cycle of manufacturing, utilization, delivery, and reclamation of goods based on a cradle-to-cradle perspective. 10. The system boundary of embodied carbon was defined clearly from EN 15978 and ISO 21930:2017 1112. When evaluating the life cycle of EC, it is imperative to meticulously delineate each phase from A to D, encompassing all upstream and downstream processes spanning from raw material acquisition to disposal. However, it is crucial to shift the current practice of demolishing buildings towards deconstruction during their end-of-life phase 13. ISO/FDIS 59004 defines key terminology, principles, and guidance to a circular economy; ISO/DIS 59040 provides the product circularity data sheet, while ISO/FDIS 59020 provides the framework for measuring and assessing circularity performance. The Circular Economy Action Plan (CEAP), launched in 2020 by the European Green Deal, introduces legislative and non-legislative measures along the entire life cycle of products 14. It establishes principles of sustainability, encompassing enhancements in product durability, reusability, upgradability, and reparability. It also encourages the adoption of product-as-a-service models and facilitates the digitalization of product information through mechanisms like digital passports. This practice has resulted in the creation of a diverse range of distinctive documents including interinstitutional agreements, resolutions, conclusions, communications, green papers, and white papers.

The barriers are also significant, as well as the advantages of circular reactions, models, and processes, such as technical barriers, normative and cultural problems, data availability and digital resistance, etc. It shows about 69% of the published research did not consider waste management at all 9. In response to the barriers, there are four types of building circular economy practices: closed-loop recycling, open-loop recycling, design for disassembly (DfD), and refurbishment 15. ISO 20887:2020 provides an overview DfD principles and potential strategies for integrating these principles into the design process. Business model innovations to enable secondary material use involve establishing key partnerships to access secondary materials 16. In recent years, there has been a growing interest in articles about prefabricated buildings because they align with the principles of DfD, allowing for efficient demolition and preservation of building components for future use, thus achieving material recycling.

2.2 Current methods and tools for calculating embodied carbon

The calculation methods for life cycle carbon footprint typically consist of three approaches: bottom-up (process-based), up-to-bottom (economic input-output), and hybrid 17. Several studies have shown that most variations among LCA studies arise from the differences in the system boundary and scope 18. However, there is no recognized worldwide circular economy assessment framework for the built environment 15. Most simulation software adopts a process-based LCA method and is developed according to the LCA approach specified in ISO 14040/14044 and PAS 2050 19. The wide range of choices and assumptions made in different studies significantly affects outcomes, so building typology, scope, assumptions, system boundary and climate must be given when comparing LCA outcomes from different studies 20.

Numerous LCA tools and softwares are available to assist in calculating OC and EC emissions. The simulation tools capable of calculating EC are summarized in Table 1. Some softwares are applied only in specific regions (e.g., BESLCI), and some other integrated software, on the contrary, can be used in multiple countries. For instance, the building circularity add-on for One Click LCA software, used in over 100 countries, offers an alternative measure of CE using a bill-of-materials, the share of these that are renewable, reused, and recycled, and each material's proposed end-of-life process 21. Some tools (e.g., BHoM, Athena, GaBi, Pathfinder) are linked to authorized carbon emission factors (e.g., EPD, ecoinvent, ICE database). Some tools can be visualized by a diagram or building 3D modeling (e.g., One Click LCA, Tally, Beacon, LCADesign). Some computational software such as Gabi, SimaPro, OpenLCA, CLEAR, Umberto, among others, are specialized tools for calculating LCA comprehensively, in addition to estimating EC, these software packages are also capable of calculating OC. The need to verify the accuracy of the proposed estimation methods, as well as modify the existing methods to account for project-specific conditions and uncertainty, were highlighted 22.

Today, the architecture, engineering, and construction (ACE) environment demand both efficiency and quality, and Building Information Modeling (BIM) undoubtedly stands out as the epitome among contemporary architectural software solutions. BIM is defined as a set of interrelated policies, processes, and technologies that generate a systematic approach to managing the critical information for building design and project data in digital format throughout the life cycle of a building 23. According to ISO 21930, two major beneficial features of BIM for sustainable building design are those of integrated project delivery (IPD) and design optimization 24. More importantly, since the stage that determines the size of the carbon emissions in the entire life cycle of a building is the early design stage， advancements in BIM have helped architects and engineers to access tools that allow them to analyze energy efficiency measures and integrate them into their designs. Akanbi et.al. 25 created a BIM-based tool for estimating the salvage performance of buildings from the design stage. It is expected that a more complex green BIM model will generate vast amounts of data and that greater information storage capacity will be required for adequate monitoring and managing of a building's sustainability performance 26, so that the concept of circular economy can be introduced into the design of sustainable architecture.

3 Methodology

3.1 Procedure of selecting papers and cases

This paper systematically reviews all cases published in the past 20 years related to calculating the EC emissions of buildings. It is imperative to delineate the scope and selection criteria for the research cases. This paper aims to identify the most effective tools and methods for assessing the EC emissions of the whole building life cycle, and to ascertain the most widely applicable, accurate, and practical instruments by examining the LCA methods and construction stages to which these tools are applied. Through a comprehensive analysis of their strengths and weaknesses to evaluate the current carbon emission calculation methods for materials' circular transition and assess the recycling status of building materials, to provide more optimized design decisions for early-stage building recycling.

Following the target above, a systematic literature review was conducted to gather all methods for calculating EC in buildings, refer to Figure 1 for the process of literature screening. This classification was examined from four perspectives: circular economy assessment rate, calculation methodologies, application of calculation tools, and building material recycling rate. A strict search process was employed based on the checklist provided by PRISMA, which aimed to ensure the accuracy of search results and minimize any potential biases. Significantly, the advent of scientific databases like Scopus and Web of Science has greatly aided in obtaining extensive amounts of bibliometric data. This study utilized the following keywords to define the search scope: (carbon OR "carbon emission" OR "CO2 emission" OR "carbon footprint" OR "GHG emission" OR "greenhouse gas emission") AND building* AND "embodied carbon", then conducted searches on the Scopus and Web of Science Websites. The search terms were limited to articles, including article titles, abstracts, and keywords. The time period was set during past 20 years, from 2004 to 2024, with document type limited to articles and language limited to English. The retrieved articles were consolidated,

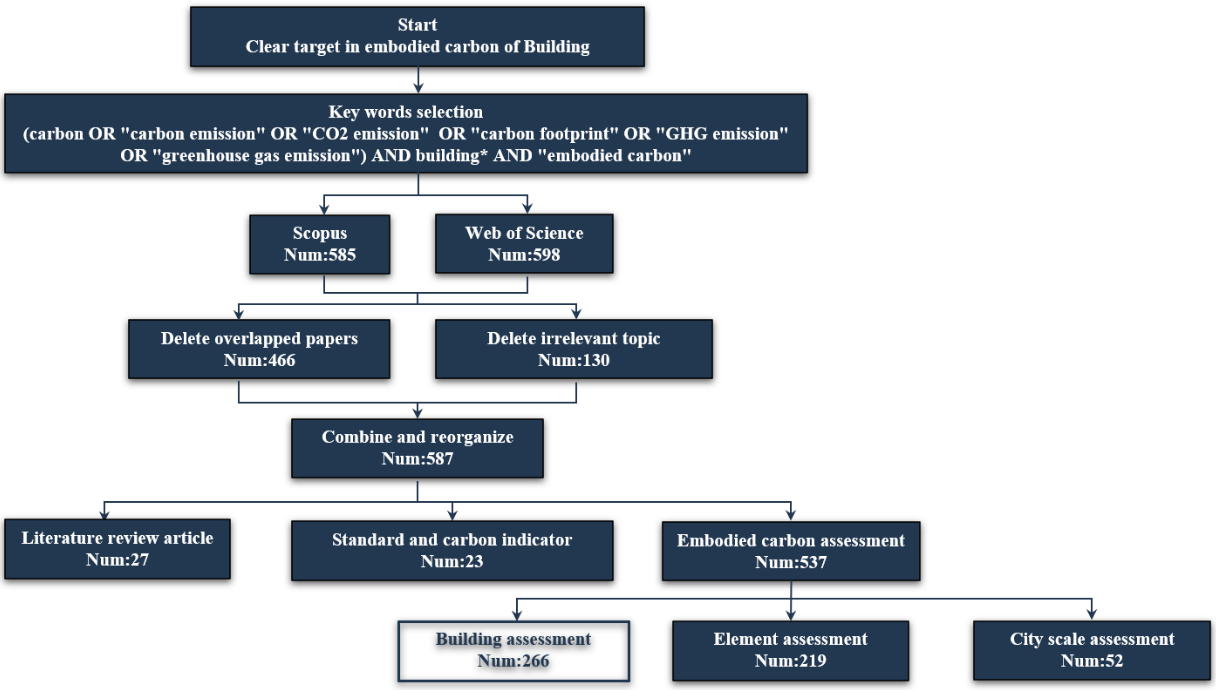

Fig. 1. Procedure of filtering paper of embodied carbon of building in the year 2004-2024.

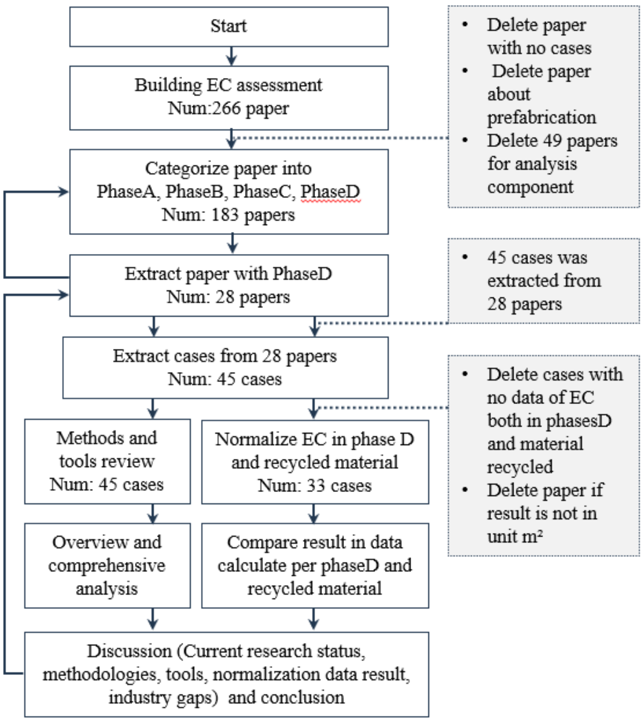

Fig. 2. Workflow of systematic review.

with 466 duplicates removed and 130 irrelevant ones eliminated, resulting in 587 articles remaining. A rapid review of the content facilitated the categorization process, identifying 537 articles relevant to calculating EC in buildings. Further refinement was conducted based on the scale of the research subjects, leading to the extraction of 266 articles specifically addressing the computation of EC emissions for individual buildings. The review will be scrutinized both in quantitative and qualitative.

3.2 Detail analysis of published cases

The specific classifications and quantities are detailed in Figure 2. The scrutiny of 266 articles on building assessment necessitates alignment with the system boundaries outlined by ISO 21930 and EN 15978:2011. The EC assessment is divided into four stages: production stage (A1-A3), Construction stage (A4-A5), in-use stage (B1-B5), end-of-life stage (C1-C4), and beyond life cycle stage (D1-D2). This paper examines how reuse, recycling, and carbon recovery of building materials can be addressed in the beyond life cycle stage. Therefore, case analysis will be conducted for all cases which are including stage D. After filtering the 266 cases to remove articles lacking building cases and those focusing on prefabrication research and simply analyses building component, there are 183 articles remain. The 183 articles were categorized and organized according to different stages, and articles containing phase D were carefully reviewed. The review results revealed that there are only 28 articles containing Phase D, from which 33 cases were extracted. Next, each case's calculation method and application tools were documented, along with the carbon reduction measures taken for each material during the recycling phase. The second step involved normalization. Articles containing data results were selected. Since the calculation functional unit used in most articles is m2, m3 and kg, the extracted articles also needed uniform units. The first set of data extracted was the EC emissions at each stage of the LCA, followed by data on the carbon emissions saved by different materials through recycling and reuse.

4 Results

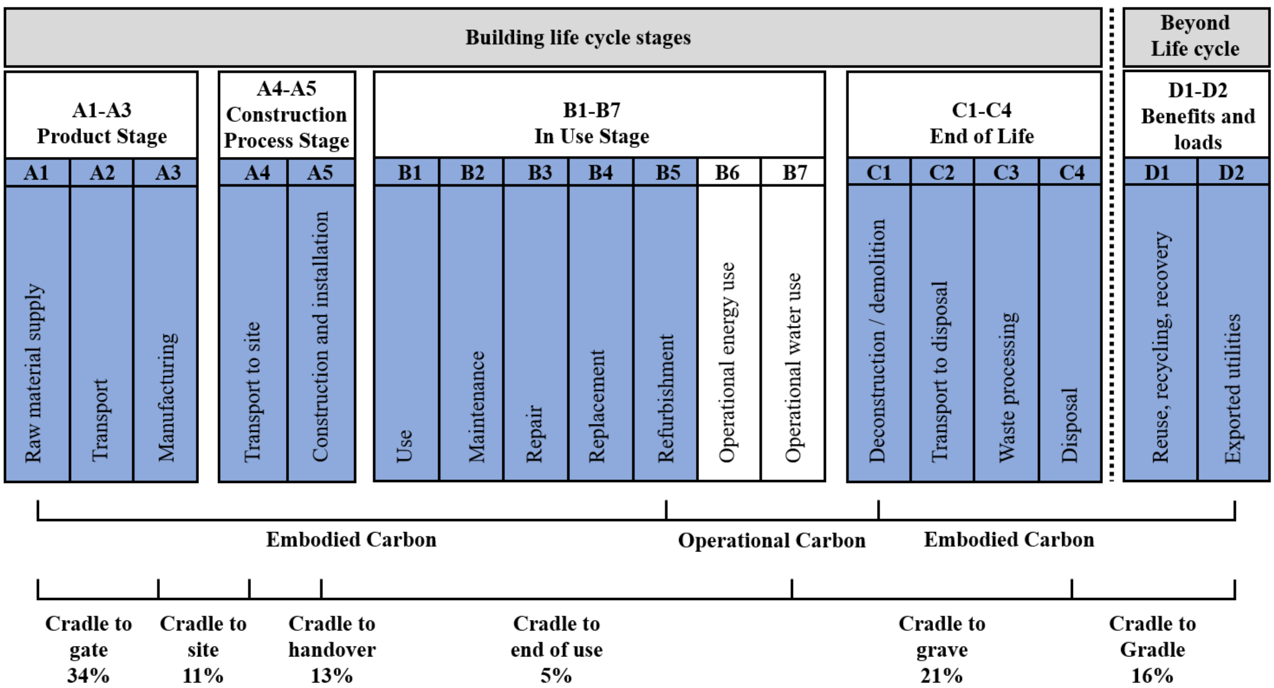

Fig. 3. Result of paper with embodied carbon analysis in different LCA stages.

4.1 Report EC results from the published paper

The papers analysing EC and building material recycling were filtered using the method outlined in section 3.2. In the selection of 183 papers, a total of 28 paper is including the phase D in their LCA research methods, which is taking 16% of all papers. Among these 28 papers, 45 case studies were collected. The results of all articles surveyed are depicted in Figure 3. Over half of the studies concentrated on the product and construction stages (A1-A5), which accounted for 58% of all papers. Similar findings were observed in the study by Pomponi and Moncaster, where they found that the end-of-life stages (C1–C4) and stage D, which address the benefits and costs after the end of a building's life, were covered in less than one-third of the papers.

4.2 Tools for assessing building life cycle embodied carbon

Among the 28 articles discussing the EC of building recycled materials, 16 articles utilized calculation tools, as illustrated in Table 1. The most commonly used tools for calculating EC were Athena, SimaPro, and Tally. Athena and Tally are freely available to users, whereas SimaPro charges for partial functions. Athena is relatively simple and user-friendly, particularly for non-experts in carbon assessment, but it is customized for various regions in North America, which limits its database's applicability. SimaPro, utilized in over 80 countries, offers greater flexibility in handling complex building models, albeit it is operationally complex, time-consuming, and labor-intensive, making it less user-friendly for non-carbon experts. Tally is a BIM-based simulation software that can extract information from building models as a plug-in tool for Revit. It boasts the most intuitive user interface and visualizations, aiding users in better understanding assessment outcomes. Tally's data sources are abundant and reliable, ensuring high data accuracy and credibility. However, it involves complex carbon emission calculation models and methods, requiring time to learn and manipulate, it is also necessitating payment for purchase. Besides the bussiness tools, some researches have also developed novel calculation methods. Tingley et al. 39 propose a methodology for conducting LCA research on reused materials or products/buildings that

Table 1. Publish paper with cases using auxiliary tool for assessing embodied carbon of recycled materials.

Case studies calculating embodied carbon with auxiliary tools in phase D							
Paper	Region	Building type	Lifespan	Stage	Main structure	Methods	Auxiliary Tool
Sansom et al. 28	UK	Commercial	-	A1-D	-	Bottom-up	CLEAR
Chen et al. 30	USA	Commercial	60	A1-D	-	Bottom-up	Athena Impact Estimator(IE4B)
Martínez-Rocamora et al. 31	Spain	Residential	-	A1-D	Reinforced concrete	Bottom-up	Revit+Tally, RF ML algorithm
Ma et al. 32	USA	Office	100	A1-D	Reinforced concrete and steel	Bottom-up	Revit+Tally
Dani et al. 33	New Zealand	Residential	90	A1-D	Timber and steel	Bottom-up	LCAQuick V3.4.4
Keskin et al. 34	Turkey	Residential	50	A1-D	Reinforced concrete	Bottom-up	AIEB,TRACI
Blay-Armah et al. 35	UK	supermarket	-	D	Steel	Bottom-up	Revit
Luo et al. [36]	UK	Office	-	A1-A3,C1-D	Concrete	I-O	PSO algorithm
Ajayi et al. 37	-	Office	30	A1-D	Brick/block	Hybrid	Revit, BIMWASTE tool，ATHENA Impact Estimator
Temizel-Sekeryan et al. 38	USA	Office	100	A1-A3,D	-	Bottom-up	SimaPro Professional v7
Tingley et al. 39	-	-	100	D	-	I-O	Sakura
Fregonara et al. 40	Italy	Office	30	C1-D	-	Hybrid	Designing out Waste Tool (DoWT)
Su et al. 41	China	Hotel	70	A1-D	Reinforced concrete	I-O	SimaPro 9.0
Deng et al. 42	China	-	-	A1-D	-	I-O	BIM, IFC
Dolezal et al. 43	Austria	Residential	100	A1-D	Concrete	Hybrid	Eco2soft
Greene et al. 8	USA	Office	100	A1-D	structural steel，mass timber	Hybrid	Waste Reduction Model (WARM)

integrate design strategies to enable easy dismantling, thereby promoting future reuse opportunities. The similar methodology has been used within the LCA tool Sakura. Sakura is specifically created for designers to explore the benefits of design for deconstruction for the structure of their projects. Fregonara et al. 40 proposed a methodology for supporting decision making in design activities based on a conjoint "economic-environmental indicator". The assessment of building scores is conducted by evaluating the relationship between environmental indicators and economic costs.

BIM is playing an important role when it comes to assessing building LCA. In order to simplify the calculation, Giaveno et al. 44 focuses on integrating the Environmental Product Declaration (EPD) data with parametric and computational procedures, it facilitated the computation of EC and embodied energy while developing a user-friendly interface for result retrieval. There exist BIM-based simulation software that enables the direct extraction of building material quantities from BIM models, providing real-time data feedback based on model adjustments. Establish linkage between the operation phase and the corresponding embodied phase of the building by using the plug-in LCA module, Tally, to compute environmental emissions from different phases of the building life cycle, including disposal 45. The IFC defines the basically underlying information needed as data input in calculating EC, including four parts: (1) Fundamental information; (2) Geometric information; (3) Position information; (4) Material information. Deng et al. 42 proposed a design software that allows to import BIM models into the EC calculation software through IFC for integration and calculation, after providing the low-carbon options and recalculating the under low-carbon measures to optimize the design scheme. A key output from this work was the establishment of a workflow that enabled iterative design feedback.

The emergence of artificial intelligence has propelled research into the embodied carbon of buildings into a new domain. Machine learning (ML)'s greatest advantage lies in its ability to learn patterns and classifications from vast amounts of historical data, organizing data through various mathematical formulas. As new data surfaces, it assimilates this information based on past occurrences, thereby predicting future trends. In the application of EC research, the most prevalent ML algorithms are support vector machine (SVM), regression model, random forest model (RF) and artificial neuron network (ANN). In the examination of building recycling cases, according to the study conducted by Martínez-Rocamora et al. 31, it was observed that the regression model exhibits potential in predicting the environmental consequences of upcoming construction projects and can be effectively employed for analyzing larger urban areas. Regarding the optimization of EC in early-stage building design, various optimization models exist, such as the PSO algorithm and Montecarlo analysis. However, the drawback of ML lies in its requirement for extensive data to train models, which poses significant challenges for complex engineering projects like construction, involving multiple stakeholders. This difficulty arises from incomplete data collection and the reliability of data sources. Therefore, the application of BIM in construction becomes particularly important. Serving as an information integration platform, the assistance of BIM provides a digital environment that elucidates the complexity of assets' elements and system boundaries 46. Consequently, within the construction industry, a call for data becomes imperative 47. Ensuring transparency in the information used to calculate carbon emissions while simultaneously providing data support for future carbon emission predictions both in the small and large scale of architectures.

4.3 Normalization of embodied carbon by LCA phases

The data was extracted from published papers, of which 82% were sourced from the past 5 years, indicating an increasing recognition of the significance in addressing carbon emissions associated with recycling and utilizing building materials, as well as highlighting their potential for future research. Among the 28 articles containing phase D, a total of 45 cases with valid information were collected. Although these cases exhibit variations in their research scope, they all provide insights into the EC emissions of each stage of LCA. Since the functional unit used in most cases is m2 gross floor area (GFA), the results of EC in this study are expressed in m2 rather than m3 or kg. The normalized results are illustrated in Figure 4 and Figure 5. It demonstrates the range and average values of EC at each stage, highlighting that the production and construction phases contribute the most to EC emissions. According to Figure 4, the average emissions in stages A1-A3 are 306.8 kg CO2e/m2, accounting for approximately 74.45% of the total EC emissions over the building's lifecycle. Following closely are the maintenance stages (B1-B5) and end-of-

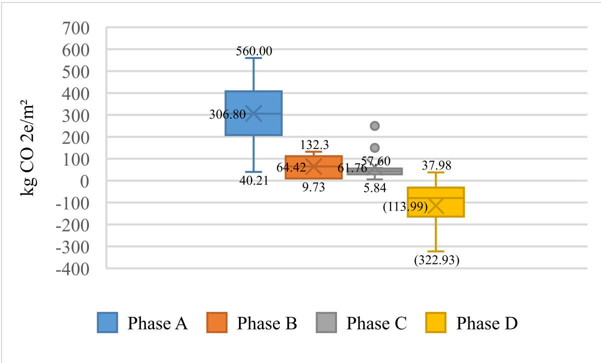

Fig. 4. Distributions of EC emissions under LCA different stages.

life stages (C1-C4), with average EC emissions of 64.42 kg CO2e/m2 and 61.76 kg CO2e/m2, respectively, representing an average of 10.45% and 13.35% of the total. In the beyond life cycle stages (D1-D2), the EC emissions offset by the recycling and reuse of building materials result in an average offset of -133.99 kg

CO2e/m2, constituting approximately 16.85% of the entire lifecycle.

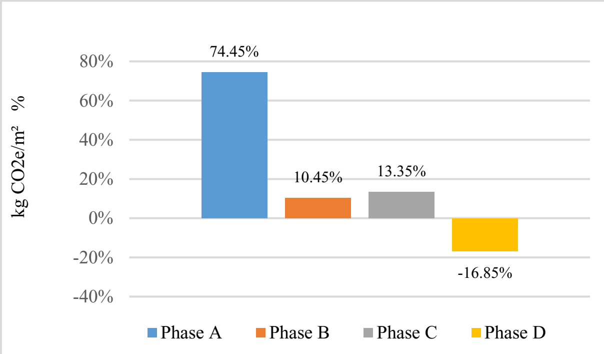

Fig. 5. The proportion of embodied carbon emissions at each stage to the total life cycle emissions.

In stage D, which involves material recycling and reusing, the EC emissions of buildings are subject to significant variations, particularly concerning the primary materials used in the construction and the building's main structural components. Considering the utilization and recycling of materials, further analysis was conducted on the material recovery rates from the past 28 papers related to phase D. The result of normalization of each materials in shown in Figure 6. The statistical results indicate that the primary materials targeted for recovery in the cases are steel, concrete, timber, and metal. Brick and masonry are not within the scope of this study due to the lack of available data. Among these, steel and timber exhibit the highest carbon offset from recycling, with average offsets number of -183.86 kg CO_{2e}/m^2 and -84.13 kg CO_{2e}/m^2, respectively. Metals such as aluminium also show relatively high recycling rates, resulting in a carbon offset of -32.6 kg CO_{2e}/m^2. Concrete demonstrates the lowest recycling rate, thus resulting in the least amount of carbon offset with an average number of -2.39 kg CO_{2e}/m^2.

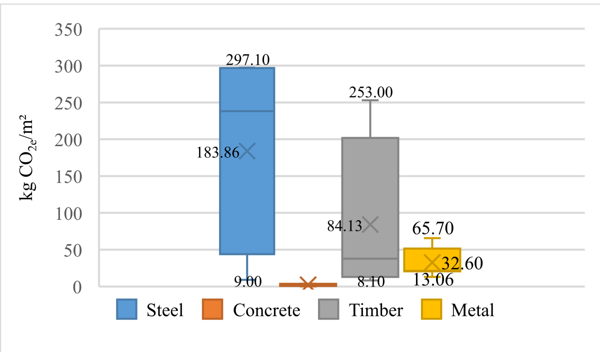

Fig. 6. The result of carbon emissions offset in the recycling phase D of materials.

4.4 Low-carbon strategies in achieving material circular economy

4.4.1 Strategy 1: select high-grade low carbon and secondary materials

Using high-grade products (materials with high durability) with high-recycled content (create demand for recycled and secondary materials in closed loops) gives significant reduction on EC. It can prolong construction's life span, thus contribute to waste prevention and lower EC emission per unit. The utilization of secondary materials in the construction of buildings results in a decrease in energy consumption for new processes and a higher level of environmental benefits, as opposed to buildings constructed using primary raw materials 48. Designers and other members of the project team are required to take into account strategies aimed at minimizing the amount of energy consumed during the construction phase of buildings 37. Compared to steel, the recyclability of concrete is limited. However, measures can be taken to reduce the EC emissions of concrete, such as minimizing the use of cement and incorporating additives into aggregates to enhance the structural performance of concrete 49. Utilizing lightweight concrete to minimize the quantity of concrete used and optimize a building's structural system can greatly contribute to reducing both the environmental impact and EC associated with construction 32.

Biomaterials, as a natural material, are recommended for promotion in the literature due to their sustainability and minimal impact on human health and the environment. For example, hemp was assumed to be used instead of mineral wool as an insulation material as it is a natural alternative, has lower EC, and is biodegradable. The use of plant or bio based construction materials can help to offset the environmental effects of climate change 50.

4.4.2 Strategy 2: Choose high recyclability materials - recycle, reuse, remanufacture

Research shows adopting resource recovery principle can lead to 37% GHGs reduction from building 51. Compare with recycle and landfill as two waste treatment methods for end of life of building, the recycling is the most preferable treatment approach 35. Wood exhibits excellent recycling and carbon sequestration characteristics. In line with globally recognized carbon footprint guidelines such as PAS 2050, ISO 14067, and WRI GHG Protocol for Products, it should be noted that if reforestation efforts are undertaken following logging activities, the growth of forests can result in a decrease in atmospheric carbon dioxide levels. This phenomenon is commonly referred to as negative carbon emissions. According to the research conducted by Chen et al. 30, taking into account the carbon stored in cross-laminated timber (CLT) used in construction, the reduction in GHG emissions would increase to 69.5%. This comparative analysis highlights CLT as an intelligent alternative for structural components like walls and floors, when compared to conventional building materials such as concrete and steel. Steel has considerable contribution to the EC because of hot-dip galvanization during production processes while it also has a higher recyclability ability 34. Dani et al. 33 found that the light timber house had around 50% fewer carbon emissions than the light steel house during its material production stages. However, the carbon offset from the light steel house was twice as high as the light timber house.

4.4.3 Strategy 3: Design for deconstruction and materials recovery

Developing designs that facilitate the disassembly of construction products, enabling easy separation into reusable components and promoting reassembly, reconfiguration, and recycling. According to Morales-Beltran et al. 52, the incorporation of disassemblable timber components in the redesign of a hybrid steel-timber residential building, along with the consideration of carbon sequestration factor, facilitates progress towards achieving the zero-carbon emissions target. Similar findings are provided by Greene et al. 8, the research shows the emissions from the production and transportation of all building materials can be almost entirely offset (98% reduction) by the biogenic carbon embodied in the timber products if timber products are re-used following deconstruction. Regarding to evaluate recovery potential of building components, Cottafava et al. 53 developed a new disassembly criteria，which are Types of connection, Connection Accessibility, Crossings, and Form Containment. Joensuu et al. 54 encourages the construction sector to think of buildings as a set of separate product systems with potential for reuse and created a new method for buildings' LCA to account for the benefits of design for disassembly components. The DfD makes the components to be recycled easier. This step can also selectively demolish materials by level of hazard and increase source separation into high-value, pure material fractions.

4.4.4 Strategy 4: carbon capture, utilisation and storage (CCUS)

CCUS is a technology and method aimed at reducing atmospheric CO_2 emissions by capturing, utilizing, and/or storing CO_2 generated during industrial processes. For the first time in almost a decade, 2018 saw an increase in plans to develop large-scale CCUS facilitie 55. A CO_2 utilization technology called CarbonCure, was considered in Temizel-Sekeryan et al. 38's study. CarbonCure injects post-industrial CO_2 into concrete during the mineralization phase to reduce the need for cement. This process also helps to permanently embed CO_2 in concrete as a form of mineral. The CO_2 stored in the form of carbon in the timber itself (around 50%), leads to a net negative GWP. In the central Europe building design, more carbon is stored in the mass timber building than is released (fossil and biogenic based) during production (A1–A5) 43. Renewable energy is also an important alternative means of decarbonizing material production.

5 Discussion

This paper adopts a systematic review and meta-analysis approach to investigate how methodologies and tools impact the assessment of EC in buildings with the aim of achieving the circular economy. A total of 266 articles related to building embodied carbon published between 2004 and 2024 were screened, from which 45 cases involving the calculation of material embodied carbon in phase D were identified. By comparing different cases based on a consistent variation, the study ensured that results could be compared on the same dimension. Following the collection of result information and data, several key findings emerged from the study.

Firstly, although the quantity of research on EC emissions is significantly less compared to OC emissions, there has been a gradual increase in research output in recent years. However, regarding the EC emissions of building life cycles, this topic encompasses a wide scope of content, involves complex methods, and faces numerous obstacles. These obstacles include variations in calculation methods (bottom-up, input-output, hybrid), differences in regulations across regions, diverse sources of EC emission factors, utilization of different tools, and the lack of data in bill of quantities, resulting in disparities in results and the inability to establish unified measurement standards globally. Research on carbon emissions in LCA Phase D remains scarce, constituting only 16% of all articles. Only a limited number of studies have assessed the entire life cycle of conventional buildings from a cradle-to-cradle perspective, aligning with the findings of Ghisellini et al. 56 This research also indicates that 58% of papers focus on reducing EC in materials during the production and transportation processes. Specifically, only 16% papers consider building material recycling in the early design stages, missing the critical period for determining material end-of-life treatment. Therefore, this paper advocates for stakeholders in the building sector to prioritize building material reuse in early-stage design and integrate it into the assessment of the building's entire life cycle.

Secondly, the results of normalization indicate that material production and construction have the highest EC emissions, followed by end-of-life and maintenance. The carbon emissions offset during the material recycling and reuse stage are particularly crucial in the context of the circular economy, with an average offset of -113.99 kg CO_{2e} /m^2, accounting for 16.85% of the entire lifecycle. In the process of building material recycling, steel, concrete, timber, and metal are frequently mentioned as recycled materials, with steel having the highest offset at -183.86 kg CO_{2e}/m^2. The range of steel's offset in the studied cases varies from -9 to -297 kg CO_{2e} /m^2. The material with the lowest recycling rate is concrete, with a carbon offset of only -2.39 kg CO_{2e}/m^2. This is mainly due to concrete being the most widely used material, yet its recycling process is complex and economically costly, thus limiting its recycling and reuse. In the calculation of the entire life cycle carbon footprint of buildings, there are many factors that can affect the results, including material selection, sources of carbon emission factors, building GFA, and building lifespan. For instance, Pan et al. 19

concluded after comparing 244 cases related to EC that the assessment of EC is highly dependent on the building's lifespan. The longer the lifespan, the lower the average EC of the materials per unit.

Thirdly, in terms of the calculation methods and simulation software for EC in buildings, traditional manual methods are predominantly utilized, where calculations are conducted stage by stage. For the recycling stage of buildings, the most commonly used tool is the Athena Impact Estimator， TallyLCA, SimaPro. Some tools are user friendly and designed for none expert such as Athena, whereas SimaPro and TallyLCA is more time consuming to learn how to use as well as input all the building data. The BIM plug-in module TallyLCA was used for life cycle assessment, which would omit additional manual input of data. Despite the widespread approval and usage of EC impacts estimator in building simulation and LCA, it should be emphasized that the precision of simulated outcomes is heavily reliant on the choice of tools 37. It was found that clearly, narrating measurements on the benefits of circularity concerning emissions is a complicated task, mainly due to a lack of unified metrics and interpretation. Therefore, a standardized measurement is required to provide accurate information on emissions 57, so that the result can be normalized and compared.

Finally, in order to minimize the EC of buildings during the early stages of architectural design, it is essential to plan the selection of building materials in advance and consider their reuse and recycling at the end-of-life stage. Through the synthesis and analysis of published cases, four main strategies for carbon offsetting of building materials have been identified: (1) Select high-grade low carbon and secondary materials. (2) Choose high recyclability materials - recycle, reuse, remanufacture. (3) Strategy 3: Design for deconstruction and materials recovery. (4) Carbon capture and sequestration technology. Therefore, it is crucial to consider the entire lifecycle, including the beyond-life-cycle stage of material reuse, during the early design stages, aiming to achieve a cradle-to-cradle closed-loop supply chain for materials.

6 Conclusion and future work

Although recent research has increasingly focused on reducing the EC emissions of building materials, the majority of studies have concentrated on the production stage of materials, with very few studies investigating the EC emissions generated during the end-of-life and recycling stage of building materials. The recycling of building waste hold significant potential for carbon offsetting and future research opportunities. To date, there is no unified global framework for calculating the carbon emissions of material recycling. This diversity in calculation methods and tools across each case means that the accuracy and reliability of calculation results cannot be guaranteed. In response to this barrier, it is essential to establish regulations and standards for low-carbon material recycling methods in the future. To promote the diffusion of circular design practices, it will be necessary to provide information, already at the early-design stage, about cradle-to-cradle dismantling, recycling schemes and their impact on carbon emissions.

Yangxiaoxia Li: Conceptualization, Methodology, Investigation, Validation, Data curation, Writing – original draft, Writing – review & editing. **Gabriele Masera:** Conceptualization, Methodology, Writing – review & editing, Supervision.

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

Data will be made available on request.

The work was supported by grants from the Chinese Scholarship Council award to Yangxiaoxia Li [File No.: 202308310053] for 4 years of Ph.D. study at the Politecnico di Milano, Italy.

References

1. U. N. Environment, Emissions Gap Report 2023, UNEP - UN Environment Programme. Accessed: Feb. 21, 2024. [Online]. Available: http://www.unep.org/resources/emissions-gap-report-2023
2. IPCC, Geneva, Switzerland., Intergovernmental Panel on Climate Change (IPCC), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647
3. "Energy Efficiency 2022 – Analysis," IEA. Accessed: Feb. 21, 2024. [Online]. Available: https://www.iea.org/reports/energy-efficiency-2022
4. V. Rodrigues, A. A. Martins, M. I. Nunes, A. Quintas, T. M. Mata, N. S. Caetano, LCA of constructing an industrial building: Focus on embodied carbon and energy. En. Pro. 153, 420–425 (2018). https://doi: 10.1016/j.egypro.2018.10.018.
5. EU. Buildings and construction - European Commission. Accessed: Apr. 28, 2024. [Online]. Available: https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en
6. L. F. Cabeza, L. Boquera, M. Chàfer, D. Vérez, Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis. En. Build. 231, 110612 (2021). https://doi:10.1016/j.enbuild.2020.110612
7. G. Kang, T. Kim, Y.-W. Kim, H. Cho, K.-I. Kang, Statistical analysis of embodied carbon emission for building construction. En. Build. 105, 326–333 (2015). https://doi: 10.1016/j.enbuild.2015.07.058
8. J. M. Greene, H. R. Hosanna, B. Willson, J. C. Quinn, Whole life embodied emissions and net-zero emissions potential for a mid-rise office

building constructed with mass timber. *Sustain. Mater. Technol.* 35, e00528 (2023). https://doi: 10.1016/j.susmat.2022.e00528

9. Md. U. Hossain, S. T. Ng, Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. Jour. Clean. Prod. 205, 763–780 (2018). https://doi: 10.1016/j.jclepro.2018.09.120
10. P. Ghisellini, M. Ripa, S. Ulgiati, Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. Jour. Clean. Prod. 178, 618–643 (2018). https://doi: 10.1016/j.jclepro.2017.11.207
11. EN 15978-Sustainability of construction works: assessment of environmental performance of buildings : calculation method, English version. London, UK: British Standards Institution, (2012)
12. ISO 21930:2017-Sustainability in building construction. Environmental declaration of building products. (2017). Geneva, Switzerland
13. B. Lei, W. Yang, Y. Yan, Z. Tang, W. Dong, Carbon Emission Reduction Evaluation of End-of-Life Buildings Based on Multiple Recycling Strategies. SUSTAIN. 15, 22. (2023). https://doi: 10.3390/su152215711
14. EU, A new Circular Economy Action Plan. Mar. 11, (2020)
15. H. Lei, L. Li, W. Yang, Y. Bian, C.-Q. Li, An analytical review on application of life cycle assessment in circular economy for built environment. Jour. Build. Eng. 44, 103374 (2021). https://doi: 10.1016/j.jobe.2021.103374
16. J. L. K. Nußholz, F. Nygaard Rasmussen, L. Milios, Circular building materials: Carbon saving potential and the role of business model innovation and public policy. Resour. Conserv. Recycl. 141, 308–316 (2019). https://doi: 10.1016/j.resconrec.2018.10.036
17. A. E. Fenner *et al*, The carbon footprint of buildings: A review of methodologies and applications. Renew. Sustain. Ener. Rev. 94, 1142–1152 (2018). https://doi: 10.1016/j.rser.2018.07.012
18. L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renew. Sustain. Ener. Rev. 29, 394–416 (2014). https://doi: 10.1016/j.rser.2013.08.037.
19. W. Pan, Y. Teng, A systematic investigation into the methodological variables of embodied carbon assessment of buildings. Renew. Sustain. Ener. Rev. 141, 110840 (2021). https://doi: 10.1016/j.rser.2021.110840
20. H. Islam, M. Jollands, S. Setunge, Life cycle assessment and life cycle cost implication of residential buildings—A review. Renew. Sustain. Ener. Rev. 42, 129–140 (2015). https://doi: 10.1016/j.rser.2014.10.006
21. C. Gillott, W. Mihkelson, M. Lanau, D. Cheshire, D. Densley Tingley, Developing Regenerate: A circular economy engagement tool for the assessment of new and existing buildings. J. Ind. Ecol. 27 (2), 423–435 (2023). https://doi: 10.1111/jiec.13377
22. A. Akbarnezhad, J. Xiao, Estimation and minimization of embodied carbon of buildings: A review. Build. 7 (1), (2017). https://doi: 10.3390/buildings7010005
23. J. K. W. Wong, J. Zhou, Enhancing environmental sustainability over building life cycles through green BIM: A review. Auto. Const. 57, 156–165 (2015). https://doi: 10.1016/j.autcon.2015.06.003
24. K.-D. Wong. Q. Fan, Building information modelling (BIM) for sustainable building design. Facil. 31, 138-157 (2013). https://doi:10.1108/02632771311299412
25. L. A. Akanbi et al., Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. Res. Conser. and Recyc. 129, 175–186 (2018). https://doi: 10.1016/j.resconrec.2017.10.026
26. A. Gillich, Embodied Carbon NZG 4/2023 (BSRIA, UK, 2013)
27. M. J. Page et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 71. (2021). doi: 10.1136/bmj.n71
28. F. Pomponi, A. Moncaster, Embodied carbon mitigation and reduction in the built environment – What does the evidence say?. Jour. Env. Manag. 181, 687–700 (2016). doi: 10.1016/j.jenvman.2016.08.036
29. M. Sansom, R. J. Pope, A comparative embodied carbon assessment of commercial buildings. Struct. Eng. 90 (10), 38–49 (2012).
30. Z. Chen, H. Gu, R. D. Bergman, S. Liang, Comparative life-cycle assessment of a high-rise mass timber building with an equivalent reinforced concrete alternative using the athena impact estimator for buildings. Sustain. 12(11), 4708 (2020). https://doi: 10.3390/su12114708
31. A. Martínez-Rocamora, C. Rivera-Gómez, C. Galán-Marín, M. Marrero, Environmental benchmarking of building typologies through BIM-based combinatorial case studies. Auto. Const. 132, (2021). https://doi: 10.1016/j.autcon.2021.103980.
32. L. Ma, R. Azari, M. Elnimeiri, A Building Information Modeling-Based Life Cycle Assessment of the Embodied Carbon and Environmental Impacts of High-Rise Building Structures: A Case Study. Sustain. 16 (2), 569 (2024). https://doi: 10.3390/su16020569
33. A. A. Dani, K. Roy, R. Masood, Z. Fang, J. B. P. Lim, A Comparative Study on the Life Cycle Assessment of New Zealand Residential Buildings. Build. 12(1), 50 (2022) https://doi: 10.3390/buildings12010050
34. F. S. Keskin, P. Martinez-Vazquez, C. Baniotopoulos, An integrated method to evaluate

sustainability for vulnerable buildings addressing life cycle embodied impacts and resource use. Sustain. 13, 18, 10204 (2021). https://doi: 10.3390/su131810204

35. A. Blay-Armah, A. Bahadori-Jahromi, A. Mylona, M. Barthorpe, An LCA of building demolition waste: a comparison of end-of-life carbon emission. Pro. Inst. Civ. Engin.-Was. Rer. Manag. (2023). https://doi: 10.1680/jwarm.22.00012
36. X. J. Luo, L. O. Oyedele, Assessment and optimisation of life cycle environment, economy and energy for building retrofitting. Ener. Sustain. Dev. 65, 77–100 (2021). https://doi: 10.1016/j.esd.2021.10.002
37. S. O. Ajayi, L. O. Oyedele, O. M. Ilori, Changing significance of embodied energy: A comparative study of material specifications and building energy sources. J. Build. Eng. 23, 324–333 (2019). https://doi: 10.1016/j.jobe.2019.02.008
38. S. Temizel-Sekeryan, F. C. Rios, F. Geremicca, M. M. Bilec, Circular Design and Embodied Carbon in Living Buildings: The Missing Potential. J. Archit. Eng. 29 (3), (2023). https://doi: 10.1061/JAEIED.AEENG-1445
39. D. Densley Tingley, B. Davison, Developing an LCA methodology to account for the environmental benefits of design for deconstruction. Build. Environ. 57, 387–395 (2012). https://doi: 10.1016/j.buildenv.2012.06.005
40. E. Fregonara, R. Giordano, D. G. Ferrando, S. Pattono, Economic-environmental indicators to support investment decisions: A focus on the buildings' end-of-life stage. Build. 7(3), (2017). https://doi: 10.3390/buildings7030065
41. X. Su, S. Tian, X. Shao, X. Zhao, Embodied and operational energy and carbon emissions of passive building in HSCW zone in China: A case study. Ener. Build. 222, (2020). https://doi: 10.1016/j.enbuild.2020.110090
42. X. Deng, K. Lu, Multi-level assessment for embodied carbon of buildings using multi-source industry foundation classes. J. Build. Eng. 72, (2023). https://doi: 10.1016/j.jobe.2023.106705
43. F. Dolezal, I. Dornigg, M. Wurm, H. Figl, Overview and main findings for the austrian case study. Sustain. 13(14), (2021). https://doi: 10.1016/j.jobe.2023.106705doi: 10.3390/su13147584
44. S. Giaveno, A. Osello, D. Garufi, D. S. Razo, Embodied carbon and embodied energy scenarios in the built environment. Computational design meets epds. Sustain. 13(21), (2021). https://doi: 10.1016/j.jobe.2023.106705doi: 10.3390/su132111974
45. Q. Tushar, M. A. Bhuiyan, G. Zhang, T. Maqsood, An integrated approach of BIM-enabled LCA and energy simulation: The optimized solution towards sustainable development, Jour. Clean. Prod. 289, 125622 (2021). https://doi: 10.1016/j.jclepro.2020.125622
46. J. Yan, Q. Lu, J. Tang, L. Chen, J. Hong, T. Broyd, Digital Tools for Revealing and Reducing Carbon Footprint in Infrastructure, Building, and City Scopes. Build. 12(8), 1097 (2022). https://doi: 10.3390/buildings12081097
47. B. D'Amico *et al.*, Machine Learning for Sustainable Structures: A Call for Data. Struct. 19, 1–4 (2019). https://doi: 10.1016/j.istruc.2018.11.013
48. E. Sicignano, G. Di Ruocco, R. Melella, Mitigation strategies for reduction of embodied energy and carbon, in the construction systems of contemporary quality architecture. Sustain. 11(14), (2019). https://doi: 10.3390/su11143806
49. M. Hossain, S. Ng, Strategies for enhancing the accuracy of evaluation and sustainability performance of building, Jour. Envi. Manag. 261, (2020). https://doi: 10.1016/j.jenvman.2020.110230
50. S. Attia, Towards regenerative and positive impact architecture: A comparison of two net zero energy buildings, Sustain. Cities Soc. 26, 393–406 (2016). https://doi: 10.1016/j.scs.2016.04.017
51. M. Hossain, S. Ng, Influence of waste materials on buildings' life cycle environmental impacts: Adopting resource recovery principle, Resour. Conser. Recyc. 142, 10–23 (2019), https://doi: 10.1016/j.resconrec.2018.11.010
52. M. Morales-Beltran, P. Engür, Ö. A. Şişman, G. N. Aykar, Redesigning for Disassembly and Carbon Footprint Reduction: Shifting from Reinforced Concrete to Hybrid Timber–Steel Multi-Story Building. Sustain. 15(9), (2023) https://doi: 10.3390/su15097273
53. D. Cottafava, M. Ritzen, Circularity indicator for residentials buildings: Addressing the gap between embodied impacts and design aspects. Resour. Conserv. Recycl., 164, (2021). https://doi: 10.1016/j.resconrec.2020.105120
54. T. Joensuu, R. Leino, J. Heinonen, A. Saari, Developing Buildings' Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components. Sustain. Cities. Socie. 77, 103499 (2022) https://doi: 10.1016/j.scs.2021.103499
55. IEA, Global Energy and CO2 Status Report 2018. Energy Demand. (2018)
56. P. Ghisellini, M. Ripa, S. Ulgiati, Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. Jour. Clean. Prod. 178, 618–643 (2018). https://doi: 10.1016/j.jclepro.2017.11.207
57. J. Dsilva, S. Zarmukhambetova, J. Locke, Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy. Hel, 9(10), (2023). https://doi: 10.1016/j.heliyon.2023.e20404