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Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy

Jacinta Dsilva [*], Saniya Zarmukhambetova, Jasmina Locke

Research Center, SEE Institute, Sustainable City, Dubai, United Arab Emirates

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ABSTRACT

The construction sector plays a significant role in contributing to greenhouse gas (GHG) emissions, necessitating effective and practical solutions. This study addresses the underutilization of Life Cycle Assessment (LCA) in the construction sector and demonstrates its benefits as a decision-making tool for mitigating embodied carbon. The research focuses on a G+2 building in Dubai, UAE, conducting LCA during the construction phases to assess embodied carbon levels. Results indicate that the careful selection of construction materials and involvement of LCA at the early stages of construction resulted in a 26 % reduction in the building's embodied carbon. The study recognizes the limitations of LCA but emphasizes its value and recommends future research to enhance its coverage of sustainability aspects. The findings highlight the construction sector's potential to overcome anthropogenic challenges through green solutions. Policymakers' support is crucial for implementing strategies that reduce the construction industry's carbon footprint and embrace a circular economy. The study contributes to the literature by bridging the gap in understanding the application of LCA in construction decision-making. It emphasizes the importance of transitioning to sustainable practices and circularity in the construction sector. By using LCA as a tool, construction professionals can make informed choices to reduce embodied carbon. This study underscores the urgency for adopting greener practices in the construction sector, leading to a more sustainable and low-carbon future.

1. Introduction

Global warming is primarily caused by the long-term build-up of greenhouse gases (GHG), which result from extensive human activities such as the burning of fossil fuels and detrimental land use changes. The exponential growth of the global population further exacerbates the situation, with the United Nations predicting a 68 % increase in urban population by 2050. Since cities are major energy consumers and contributors to GHG emissions, the International Energy Agency report (2021) [1], projected that population growth will intensify environmental challenges. The built environment plays a significant role in carbon emissions, accounting for approximately 50 % of the world's carbon emissions. This is due to the sector's high energy consumption and extensive use of raw materials driven by continuous construction activities aimed at meeting the needs of a growing population [2,3]. Additionally, the environmental impacts associated with constructed buildings remain consistent throughout their life cycles. To address these pressing

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* Corresponding author.
E-mail addresses: jacinta@seeinstitute.ae (J. Dsilva), saniya@seeinstitute.ae (S. Zarmukhambetova), jasmina@seeinstitute.ae (J. Locke).

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issues, the construction industry must prioritize resource efficiency and transition toward a circular economy [4]. This shift will facilitate the development of a sustainable, resource-conscious, and low-carbon economy. By embracing circular economy principles, the industry can reduce its reliance on virgin resources, minimize waste generation, and foster the sustainable management of materials throughout the entire life cycle of buildings [5].

The Circular Economy (CE) represents an economic system that aims at minimizing waste and maximizing the utilization of resources in contrast to the linear economy. The traditional linear economy model with its "take, make, and dispose" philosophy, has recently developed significant threats including climate change and widespread deforestation [6]. In contrast, the circular system promotes careful usage of materials, sustainable design, and adherence to the 3R principles of reduce, reuse, and recycle, all of which can minimize the negative impacts of the linear economy [7]. Morseletto (2020) [8], recommends a framework based on 10 common circular economy strategies namely recover, recycle, repurpose, remanufacture, refurbish, repair, re-use, reduce, rethink, and refuse.

Among various industries, the construction industry has been offering long-lived products with complex supply chains, playing a crucial role in the economic development of countries [9]. However, it has also been a major contributor to the unsustainable depletion of natural resources and contributing to various forms of pollution. Noticeably, the construction industry has been relatively slow in embracing the circular economy framework despite the considerable potential for reducing embodied and operational carbon using recycled materials and attaining higher sustainability [10]. This has prompted increased attention to the topic of the circular economy within the construction industry [11]. Therefore, it becomes imperative to evaluate how the construction sector can actively incorporate circularity principles and effectively reduce its carbon footprint. It is necessary to evaluate how the construction sector can work towards incorporating circularity and reducing the sector's carbon footprint. By adopting circular economy practices, the construction industry can transition towards a more sustainable future, where the extensive use of recycled materials and a holistic approach to resource management can lead to significant environmental benefits [12].

Life cycle assessment (LCA) is a widely recognized and utilized method to evaluate the environmental impacts and resource usage associated with products, services, or processes. It provides a comprehensive understanding of the entire life cycle from raw material acquisition to production and operational stages. Conducting LCA is essential for enhancing processes, enabling decision-making, and effectively reducing carbon footprints for project teams and policymakers [13]. The importance of LCA is increasingly recognized across various industries, including the construction sector. As the industry strives to mitigate the environmental impacts of buildings and materials used, LCA has gained prominence as a valuable tool [14]. However, it is important to note that while LCA is standardized by ISO 14040 (2006), defining the necessary steps, from goal and scope definition to impact assessment and interpretation, it primarily focuses on the environmental dimension of sustainability [15]. Recognizing the need to incorporate a broader concept of sustainability, including the social aspect, the concept of Life Cycle Sustainability Assessment (LCSA) was developed by Kloepfer and Finkbeiner in 2008 [16]. However, for the purposes of this paper, only LCA will be conducted, as LCSA is still in its infancy and presents challenges in terms of interpretation and result transparency [17,18].

The main objective of the study is to recognize the importance of LCA as a valuable tool in the construction sector, enabling informed decisions and driving progress toward achieving circularity. To achieve this objective, a comprehensive literature review will be conducted to gain insights into LCA's application specifically in the context of a newly constructed building, and to establish its relevance in the construction sector. Furthermore, a case study approach will be employed, focusing on the G+2 SEE Institute building located in the Sustainable City in Dubai, UAE. This case study will provide evidence regarding the selection and sourcing of materials during the construction phase, shedding light on the role of LCA in identifying building materials that effectively reduce the embodied carbon of the structure. Additionally, the study will emphasize the significance of implementing LCA to promote circularity within the construction sector. Practical implications and recommendations will be discussed, emphasizing the benefits and potential outcomes of integrating LCA into construction practices, with a focus on achieving a more sustainable and circular built environment. Overall, this study aims to highlight the vital role of LCA in the construction sector, showcasing its value in decision-making processes and its potential to drive the transition toward circularity.

2. Transition to the circular economy

The current linear model of "take-make and dispose" is contributing to an avalanche of pressure on environmental resources, therefore, a paradigm shift to the circular economy is imperative [4]. The concept can be traced back as far as 1758, however, has been termed differently at different times, therefore, it did not gain as much momentum as it is gaining in the 21st century [19]. The CE concept was conceived by Dr. Walter Stahel [9], suggesting that an economy in which waste is recycled into regenerating resources, sustainable growth, and environmental development are pursued, is the one that will achieve greater progress as well. The Emission Gap Report, 2020 [3] stressed that CE can be achieved by increasing the shelf-life and value of products, components, and materials, by using better waste and pollution management systems, and by regenerating natural resources. It is also important to integrate all the stakeholders in the value chain of materials since that can promote waste elimination by closing the materials loop [20].

The CE framework consists of three loops, namely the inner loop, green loops, and outer loops [21]. The inner loop is also known as an open loop that demonstrates the critical stages in the life cycle, in other words, the inner loop represents the take-make-dispose model i.e., linear economy. With the addition of green loops, closed-loop systems are developed after the initial consumption or use. The main aim of green loops as highlighted in Fig. 1 is to generate a system that slows, closes, and narrows material and energy loops. Slowing resource loops entails extending the useful life span of products. Additionally, the inner and green loops are part of the outer loop, which consists of materials and resource management; product research, design, and development; purchasing, standards, and certification; and sustainable consumption and demand-side management [22–24].

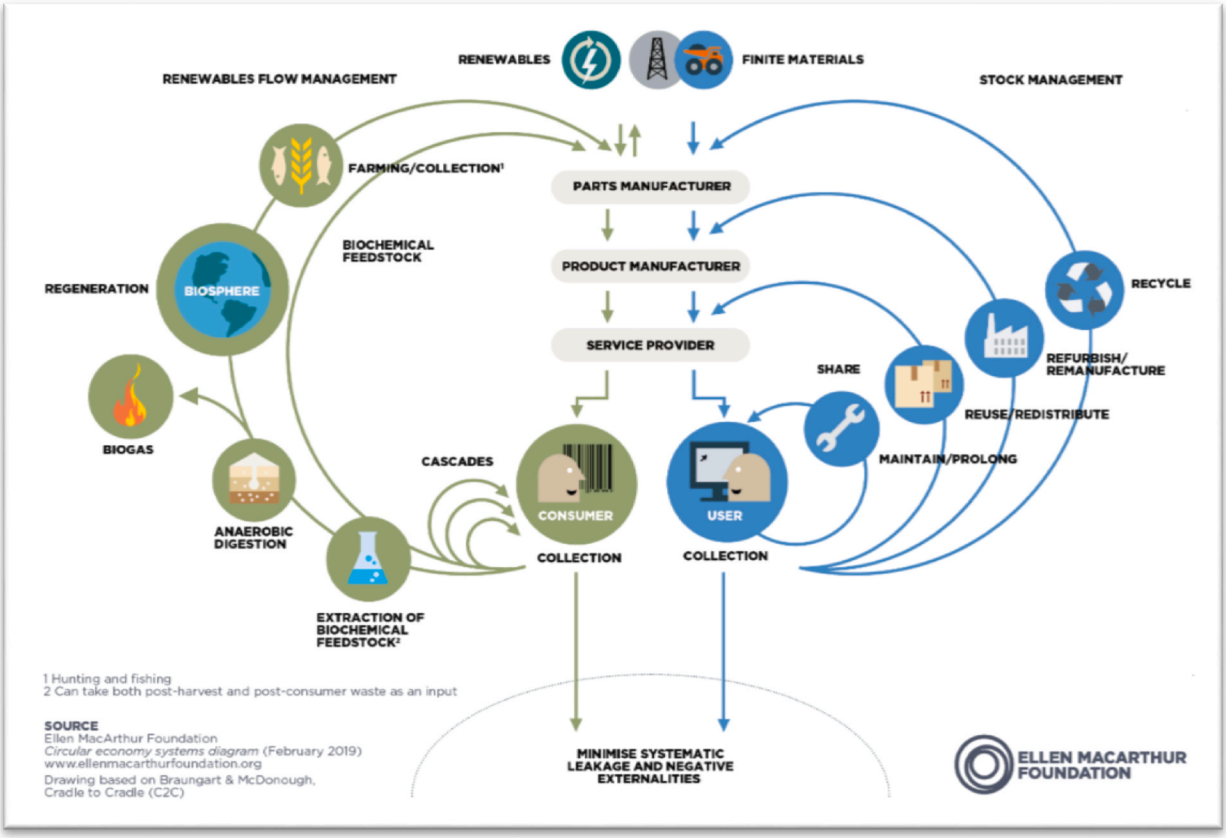

Fig. 1. Circular economy systems.
Source: (The Butterfly Diagram: Visualizing the Circular Economy, 2023) [25].

The circular economy, in other words, reduces waste, fundamentally altering the way we produce and consume, resulting in a healthier, thriving ecosystem that circulates value throughout the economy and society. In doing so, it fundamentally decouples economic growth by assessing micro, meso, and macro levels of resource consumption and recouples economic growth with societal progress, thereby providing a much-needed solution framework for addressing global challenges [26]. As it promotes waste and resource recycling, the CE represents a promising attempt to integrate economic activities and environmental well-being into society [27].

In a circular economy, as in any economy, drivers and barriers are present. Scholars have classified various barriers and drivers of achieving CE while categorizing them into internal and external [28]. Internal barriers include company policies and strategies, financial as well as technological barriers [29], and product design. External barriers cover for example consumers, social, cultural, and environmental barriers that are impediments to the implementation of CE. The driving forces of CE are fundamental to recognizing and comprehending the process [30]. Internal drivers include for example organizational drivers, resource availability and optimization drivers, financial drivers, and product design and process development, all of which support the implementation of CE [31]. Organizational drivers may include factors such as good leadership, design strategies, innovation, research and development, and organizational infrastructure [32,33]. While internal drivers are factors that impel CE practices from inside an organization, external drivers on the other hand are the factors that drive CE practices from outside of an organization, including legislative and economic factors. These drivers encourage businesses to seek out and exploit circular opportunities for competitive advantage [34].

3. Life cycle assessment and its potential in the circular economy

Life cycle analysis (LCA) is a powerful, science-based tool for measuring and quantifying the environmental and social impacts of products, services, and business models throughout their life cycle, from raw material extraction to manufacturing, distribution, use, and disposal. The idea of LCA was first discussed around 1970 and was mainly used to analyze consumer products [35]. However, over time LCA was established on ISO 14040/44 standards, which defined all the steps for its use, and its strength lay in its robustness and transparency [36]. The LCA studies often highlight the relationship between the embodied energy of the materials and its operational energy, i.e., the energy required to maintain the building and its related activities [37]. LCA can be applied to build dynamic CE strategies by evaluating the impacts on the upstream and downstream value chains. Additionally, if LCA is applied holistically it can be beneficial socially and economically since it can assist in evaluating different strategies related to material efficiency, thus advancing the transition toward a CE [38,39]. LCA has gained popularity since it is considered one of the approaches to understanding the environmental performance of products and services throughout their life cycle [40].

The application of LCA has been on the rise in several industries, particularly, construction, which is constantly growing at a rapid pace in most economies. Here, LCA is conducted to evaluate new buildings to reduce CO_2 emissions and lower energy demands at the operation stage. According to Mohan et al. (2020) [41], LCA is a well-established technique for sustainability studies in the built environment and can be extended to CE research. The LCA study has become necessary since the relationship between the embodied and the operational energy of the materials is changing in such a way that 40 % of the impact is associated with materials and 60 % is associated with the operational stage [42]. There have been several studies conducted on LCA applications in the built environment. Therefore, it is inevitable for the construction industry to consider embodied carbon in building materials along with lower energy demands at the operational stage to eventually reduce the total life cycle carbon of the buildings. Consequently, when transitioning to a circular economy, it is necessary to note that, while LCA is beneficial at pointing to the best option based on a specific metric at a specific time, it can lead to favoring short-term gain over systematic change, ignoring difficult-to-measure impacts, and decreasing the accuracy of analysis [43]. Another shortcoming could be while assessing CE strategies, technical and scientific challenges across the LCA need to be addressed as well as other larger implications faced by both emerging and developed economies [9,38].

To successfully use LCA to support and inform the transition to a CE, it is critical to recognize its limitations and treat it as one tool among many, rather than as the sole source of truth. We need to start thinking beyond just optimizing things in the current system. Instead, we should envision a circular economy as our desired state and start innovating toward that goal. This will allow us to create a more sustainable and efficient system for the future. The life cycle Initiative encourages LCA professionals to address the technical and scientific flaws in the evaluation of CE projects.

4. Circular economy in the construction sector

The construction industry has a substantial global impact, consuming around 40 % of raw materials and responsible for 39 % of total CO_2 emissions, of which at least 11 % comes from manufacturing building materials and products. This places significant pressure on the environment [44]. However, it is noteworthy that the construction industry significantly contributes to economic and social growth, by generating millions of jobs per year in every economy [45]. Therefore, the construction industry is considered to have a greater potential to move toward a circular economy approach by adopting strategies such as relying on eco-friendly products and technologies, increasing the usage of correct or recycled building materials, and reducing waste during different stages of the building life cycle [46].

A circular economy can be well aligned with industrial ecology toward construction sustainability [47] since it can utilize the principles of industrial symbiosis, which is to share resources between different sectors [48]. CE has been gaining significant momentum in the construction industry, and as per Peña et al. (2021) [41], it may provide a greater opportunity for the construction industry to reduce GHG emissions, overall energy use, and waste production. There is a possibility that by being involved in CE the construction industry might increase the use of recycled material, reuse resources and embrace more sustainable solutions despite some of the challenges of deploying CE strategies [49]. By incorporating CE strategies like the design for disassembly (DfD), there is an opportunity to reassess the current life cycle design and management of established building systems. This approach can enhance the extraction and utilization of the abundant future resources present within existing building stocks [50]. A step toward CE can significantly benefit the industry economically due to the reduction of extracting virgin materials as well as waste minimization that can be further recycled or reused [51]. Furthermore, CE not only benefits individual industries but also offers an opportunity for dialogue and collaboration between public and private sectors to develop long-term value for the economy. For example, Gulf Cooperation Council (GCC) countries realized that incorporating circular initiatives, particularly in urban areas, can contribute to saving $138 billion by 2030. The UAE has been taking concrete steps to address concerns in the construction industry by signing a pledge in cooperation with the World Economic Forum to move towards a circular economy using fewer natural resources and reducing pollution to tackle climate change issues [52].

5. Life cycle assessment in the construction sector

Even though LCA has been widely used in the construction sector since 1990 as an important tool for assessing buildings and building materials, it is less developed in comparison to other industries. However, from the beginning of the 21st century, interest in LCA has been increasing quickly. This change was noticed due to the increasing importance and trend of sustainable production and other green strategies of different countries. LCA has become one of the significant tools for monitoring the environmental impact of the materials used during construction [53]. The main challenge of using LCA as a tool in the construction sector is the complexity of building designs as well as the massive and diverse requirements of materials. It can also be challenging since the production method of each building is inconsistent and each one has its unique features. There is a limited amount of information available on the environmental impact of producing construction materials, the process of construction, and demolition which makes it hard for a company to utilize the tool in the best possible manner [54]. Therefore, in this research, the authors were cautious about the implications of using LCA however due to its enormous benefits on proactive decision-making before construction the team decided to use LCA during the initial stages of construction of the sub-structure and super-structure.

6. Methodology

A review approach was adopted to systematically analyze the existing literature using keywords such as ‘life cycle assessment’, ‘construction sector’, ‘buildings’, ‘sustainable construction’, and ‘circular economy’. The search was carried out using Google Scholar, Scopus databases, MDPI databases, and other related databases. This initial search helped in identifying and snowballing relevant research papers. Around 80 papers were identified as potential and finally, 56 papers were found to be closely related. Papers published during the last 20 years were given priority since topics like circular economy are relatively new in the construction sector as well as in sustainable development. Based on the in-depth investigation, it was identified that it would be better to utilize a case study approach to highlight the influence of LCA and circular economy on the construction sector. Therefore, the research adopted a case study method to highlight the practical application of the LCA technique on a real construction site in Dubai UAE, analyzing the materials utilized and the basic considerations of the most critical inputs in this scenario, such as steel, concrete, and other materials.

According to ISO 14040, LCA is divided into four phases i.e., Definition of the objective and scope, analysis of the life cycle inventory, evaluation of the environmental impact of the life cycle and interpretation [55], and by use of sustainable building material to reduce embodied and operational carbon. Fig. 2 below provides a graphical representation of the methodological approach of LCA leading to the circular economy that was discussed in detail in the following paragraphs.

A case study method was necessary since one of the objectives of the study was to highlight the importance of proactive decision-making during the construction phase i.e., to consume less, consume better, and create systemic change which are the principles of the circular economy that can best be explored by conducting a case analysis of a specific component or the construction phase of a building [56,57]. Therefore, in this case, LCA was conducted on the building materials used during the construction phase of a G+2 SEE Institute building located in the Sustainable City, Dubai, UAE using two business cases (Business-*as*-usual and Actual). The business-*as*-usual scenario is a baseline that tends to employ little or no efforts to limit the embodied carbon and is used to compare alternative scenarios, whereas the actual scenario reflects all the efforts taken by the project team and demonstrates the reduction of the embodied carbon of the building. The institute with all its diverse applications spans approximately 6000 m^2 of built-up area (BUA), therefore, this case is an important contribution to the existing knowledge on how a significant amount of embodied carbon can be reduced by careful consideration of the building materials and other futuristic thinking during the construction phase to enable achieving circularity in the long run.

Another important reason for conducting a case analysis was that the study was conducted in the United Arab Emirates (UAE), whose climate and geographical location put certain limitations in place. The UAE is divided into three major ecological areas, namely coastal, mountainous, and desert areas. Most of the area is covered with sand, and the general climate is arid. It has two main seasons, i.e., long dry summers and around four months of winter. The summers are accompanied by humidity levels going up to 90 % at times and high solar radiation levels. Thus, in a harsh climate like Dubai, developers and contractors are often bound to a limited choice of key building materials for foundation, structure, and enclosure [58]. With operational energy requirements in mind, they need to ensure that the building fabric or building envelope serves its primary purpose. The building envelope does the task of protecting buildings from extreme temperatures, dust, wind, and even moisture. This is where innovative solutions around building materials and products come into play [59]. Sourcing low-carbon materials for the sub- and superstructure is crucial for achieving embodied carbon objectives with narrow reduction options. Therefore, Fig. 3 highlights the components included in the foundation, substructure, and superstructure.

Low-carbon building materials and products have been the subject of research and development, and it is important to highlight how the construction industry can reduce carbon emissions by selecting the right materials. Interestingly, there are some studies conducted on supply chain and waste management of materials in the construction industry in the UAE however, there are not many peer-reviewed papers that focus on the life cycle assessment of the real construction of a sustainable building and therefore it becomes imperative to highlight the contribution by this case.

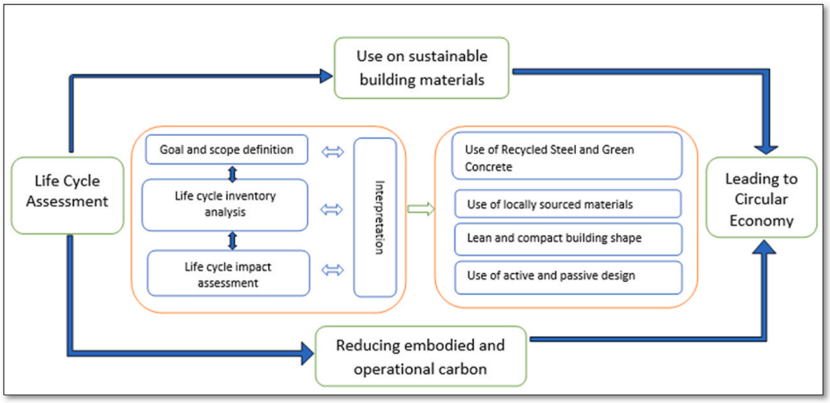

Fig. 2. Methodological approach of Life cycle assessment leading to the Circular Economy.

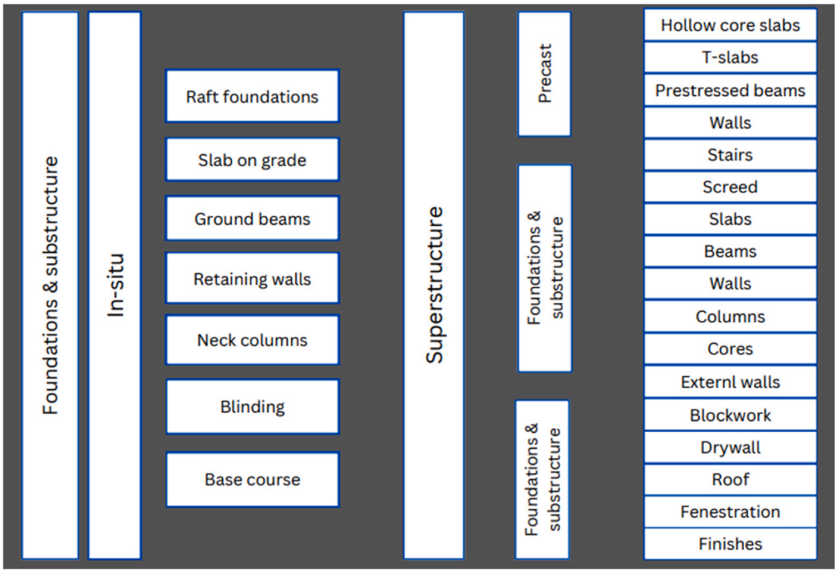

Fig. 3. The components involved in the Foundation, sub-structure and super-structure.

The scope of this study was defined as 'from the cradle to the gate', comprehending the assessment of environmental impact from resource extraction (cradle) to the factory gate (i.e., before transporting the goods to the consumers). For this case study, it can be translated as to the end of the construction phase but excluding the operational stage. The objective of the paper was to review the existing literature on life cycle assessment (LCA) and circular economy, which was completed through a comprehensive literature review. Additionally, the study focused on applying LCA to identify possible emissions and design strategies to mitigate carbon in the best possible manner during the construction phase, as well as to establish approaches to achieve a circular building. It was critical to identify the challenges of using LCA in this context, keeping in mind the complexities involved in the construction process.

The life cycle of a construction activity follows DIN EN 15804: 2020–03 [60] presented in Table 1 and consists of the manufacturing (A1-A3), which describes all processes of manufacturing including product manufacturing, and construction. (A4-A5) Is associated with the construction of the building and product installation. (B) refers to usage, i.e., the operational elements of the building including maintenance and repair, (B6 and B7) focusing on the usage of energy and water during the operational phase of the building. The disposal phases (C1–C4) describe the end-of-life stages such as the waste treatment required for recycling. (D) represents the data outside the product life cycle for example reuse, recycle and/or recover [61,62]. For this study, only A1 – A3 was reviewed since they are the largest contributor to the embodied carbon of a structure.

One Click LCA application was used to provide support to most of the results presented in the later section. One Click LCA is a cloud-based life cycle assessment (LCA) software that is used by professionals in the building sector to evaluate the carbon impact of projects in compliance with established green building rating systems. It is recognized as the highly-rated LCA software for the Building Research Establishment Environmental Assessment Method (BREEAM) and is compatible with more than 40 international Green Building certification schemes, including LEED.

7. Results and findings

This section discusses the results of LCA conducted for two building cases (Business-*as*-usual and Actual). The results are presented for the whole building, covering A1-A5 emissions; however, only major construction items and their impact within the product stage (A1-A3) were reviewed due to the limited availability of the details. The functional units in those analyses varied depending on the type of material input based on which the final information about the amount of embodied carbon generated per square meter of the built-up area (BUA) was derived. It is necessary to mention that the planning and construction team followed all the required sustainable building design and technical recommendations, and the building was constructed following regulatory requirements. The main objective of the study was to quantitatively evaluate various embodied carbon reduction measures that were implemented by the project team, highlighting the evidence collected during the construction of the G+2 SEE Institute located in The Sustainable City, at the heart of an area called Dubailand. It is conveniently situated near Dubai's most well-connected roads – Sheikh Mohammed Bin Zayed (E311) and Emirates (E611), making it an attractive and accessible destination.

The building is a multi-storey, multi-purpose structure designed to accommodate various activities and functions, such as offices, classrooms, immersive experiences, and events and conferences. It spans over 4515 sqm of gross floor area which provides ample space for its versatile operations angles. Every line, curve, and angle of the building's structure tells a story of careful planning and execution, creating a blend of form and function. Two principal building materials – concrete and steel – shaped this structure, and for several reasons.

Table 1
Building assessment Modules for life cycle assessment according to EN15804:2012 [60].

Product/Manufacture Stage [A1-A3]			Construction Process Stage [A4-A5]		Use [B1–B7]							End-of-Life Stage [C1–C4]				Benefits & Loads Beyond [D]
					Building Fabric					Operation of the Building						
Raw Material Extract/Process/ Supply	Transport	Manufacture	Transport to the Site	Assembly/ Install in the building	Use/ Application of Installed Products	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Deconstruction/ Demolition	Transport to Waste Process	Reuse-Recovery-Recycle	Display	Reuse-Recovery-Recycle Potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Cradle-to-Gate			Gate-to-Grave													
Cradle-to-Grave																
Cradle-to-Cradle																
System Boundaries																

In the arid desert climate of the UAE, engineers, architects, and designers are bound to use materials that can withstand extreme weather conditions and offer great fire resistance and structural resilience. Furthermore, the flexibility of concrete and steel enables a wide range of architectural designs and structural configurations. Finally, these are cost-effective and locally available products, with many plants catering alternative options with recycled content in response to the growing demand for sustainable building materials. The construction industry recognizes concrete and steel as a significant contributor to greenhouse gas emissions. Selecting concrete and steel with reclaimed components was the main catalyst to reduce the building's impact on the environment and climate change, as well as drive circularity.

7.1. Embodied carbon in building materials

It is necessary to understand that precast and in-situ concrete elements make up most of the overall embodied carbon of the building that comes from building materials [63]. Tackling materials with the highest emission rate is the right strategy to reduce embodied carbon effectively. Figs. 4 and 5 highlight the two scenarios used for this study showing the levels of the embodied carbon of the precast and in-situ as well as of other materials used.

The figures above highlight that 21 % of the embodied carbon comes from precast concrete, 61 % from In-situ concrete, and 17 % from other elements in the Business-*as*-usual case (**the percentages were derived by dividing the total embodied carbon from precast quantities**). Similarly, in the actual scenario, it can be noticed that the carbon footprint mainly comes from the concrete i.e., 22 % from precast and 59 % from in-situ, and only 18 % from other elements which can comprise doors and windows, lightweight façade, gypsum walls, finishes, and façade tiles. Therefore, it is necessary to understand that while selecting a specific material some decisions can be crucial in reducing the embodied carbon. Therefore, in other elements shown in Fig. 6, a lightweight façade was selected, and although it had a slightly higher embodied carbon, it had better acoustics and insulation properties which supports better performance in the long run, eventually, reducing the operational carbon of the building. Such tradeoffs are often necessary since it is important to focus on the full lifecycle of the building rather than just the embodied carbon.

It is clear in Fig. 6 that due to careful decisions such as selecting the right precast concrete, In-situ concrete, and other elements, the team was able to reduce a significant amount of embodied carbon. Precisely, 25 % from precast concrete, 31 % from in-situ concrete elements, and 25 % from other elements such as selecting green materials for doors and windows, façade, gypsum walls, and tiles as possible, all this was possible due to the use of LCA at the early stages of planning and decision making about the materials used.

The study focused purely on the comparison of the overall reduction values in percentages rather than selecting individual materials due to the complexity of the data and since the quantities of building materials are identical, and therefore it does not refer to the functional units of the considered materials. Data required for the analysis comprised the Bill of Quantities (BOQ), a list of materials and services required to perform a project, and various specification sheets for one or the other material. Table 2 below illustrates the total embodied carbon associated with the building for two scenarios, Business-*as*-usual and Actual, in absolute values per building stage and per unit of built-up area.

While life cycle assessment generally comprises a wide range of impacts associated with very diverse products, the construction sector addresses GHG emissions arising throughout the building's assembly and operation. The significance of the embodied carbon of the built assets has been historically neglected because it was overpowered by the operational side of emissions. Now, with the fact that the manufacturing of building materials contributes up to 11 % of total global GHG emissions [4], embodied carbon matters as much as the energy efficiency of buildings.

7.2. Materials: concrete and steel

Two specific products were analyzed, namely concrete, both in-situ and precast, and reinforcement steel. Using such a technique as the LCA allowed the project team to measure embodied carbon and work on the reduction efforts. LCA was conducted during the pre-construction phase, which facilitated the project team in identifying the right suppliers for different materials, particularly those suppliers that were able to provide the required information.

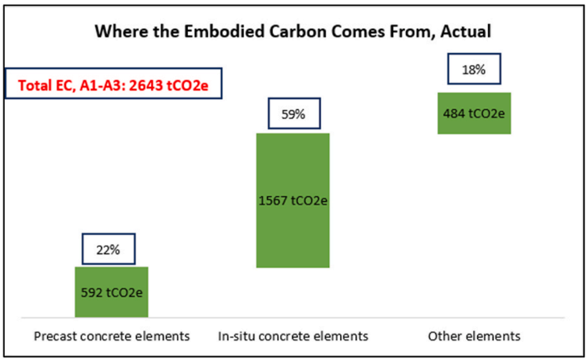

Fig. 4. Embodied Carbon identified in Actual Scenario.

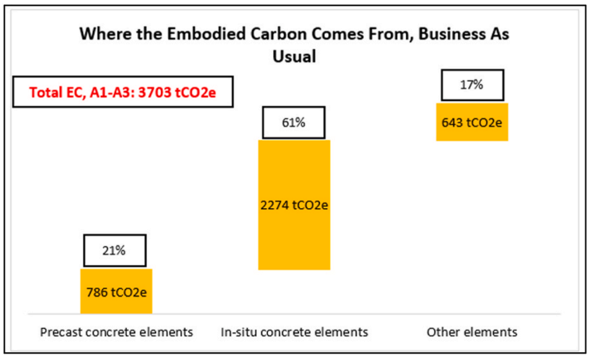

Fig. 5. Embodied Carbon of building materials in Business-*as*-usual scenario.

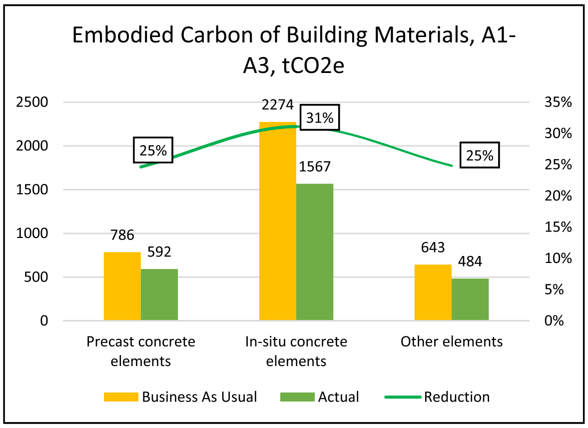

Fig. 6. Embodied Carbon in both scenarios and the reductions.

Table 2
Total embodied carbon using two scenarios.

	Business-*as*-usual	Actual
Result category	Global warming, kgCO2e	Global warming, kgCO2e
A1-A3, Construction Materials	3,704,688	2,659,181
A4, Transportation to site	63,823	62,728
A5, Construction/installation process	274,460	249,821
Total	4,042,970	2,971,730
BUA, m^2	5943	5943
EC per BUA, $kgCO2e/m^2$	680	500
Reduction achieved		26 %

Cast-in-place concrete was mostly used for foundations and blinding. The selected supplier was a well-established local firm that developed environmental product declaration (EPD) reports for several ready-mix concrete products. The reports provided transparency on which resources were used and their ratio to manufacture a certain grade of concrete, each one to satisfy the necessary certifications and standards.

There are three basic ingredients in a concrete mix – Portland cement, water, and aggregates (rock and sand). Cement is the most carbon-intensive part of the mixture; making it involves using fossil fuels for the blend of limestone and clay to undergo a process of calcination in a kiln. Moreover, this chemical reaction releases direct CO_2 emissions. Solving the cement question would greatly reduce the overall carbon footprint of concrete, and the solution needs to come from manufacturers, policymakers, and product designers. There are alternatives to cement, which include slag–scrap composites from iron and steel production, and coal combustion residuals, known as fly ash which was used in this case. As per a study conducted by Tang et al. (2021) [64], recycled aggregate concrete (RAC) can provide many benefits for large construction projects. The team used ready-mix concrete for the foundations; the slag and silica fume, which is a byproduct of producing silicon metal or ferrosilicon alloys, was used as a supplementary cementitious material. Quantities of each varied depending on the grade and application to which a certain mix was used [65].

Table 3
The incorporation of recycled content.

Material category	Industry average	Actual
Ready-mix concrete, C60	OPC +10 % recycled binders	OPC + GGBS 45 % +MS 5 %
Ready-mix concrete, C50	OPC +10 % recycled binders	OPC + GGBS 14 %
Ready-mix concrete, C40	OPC +10 % recycled binders	OPC +40 % recycled binders
Reinforcement steel	97 % recycled steel	97 % recycled steel

*OPC - Ordinary Portland Cement; GGBS - Ground Granulated Blast Furnace Slag.

Table 4
Emissions reductions using the right building materials.

Material category	Industry average	Actual	Reduction per functional unit
Ready-mix concrete, C60	442.96 $kgCO_2e/m^3$	344.7 $kgCO_2e/m^3$	22 %
Ready-mix concrete, C50	390.09 $kgCO_2e/m^3$	255.0 $kgCO_2e/m^3$	35 %
Ready-mix concrete, C40	355.83 $kgCO_2e/m^3$	262.4 $kgCO_2e/m^3$	26 %
Reinforcement steel	0.62 $kgCO_2e/kg$	0.50 $kgCO_2e/kg$	19 %

Moving on to the precast concrete, for which the supplier was different, and an environmental product declaration (EPD) was not available, the project team was provided with a letter of assurance stating the grade of concrete used for production and the percentage of recycled content in precast concrete elements and hollow core slabs. This is a common practice between the supplier and the constructors, particularly due to the trust that is developed over a long-term relationship between them.

In the absence of an EPD, which provides the most accurate information, the project team had to resort to using industry average data in both cases – for Business-*as*-usual and actual scenarios. However, the team also agreed that it is important to deal with suppliers who can provide EPD or letters of assurance to be accurate in measurements and to at least have the right assumptions in the case of the letter of assurance.

Steel is one of the world's most important engineering and construction materials. It is used in almost every aspect of a human's life, from cars and ships to home appliances and utensils. Steel is an essential construction product; buildings rely on steel reinforcement to gain strength and the ability to withstand the load. Manufacturing steel is a complex and energy-intensive process to extract iron from iron ore and turn iron into steel – more than 85 % of the energy used comes from fossil fuels. Steel scrap is an incredible metal since it is 100 % recyclable. It can be reused many times without losing its metallurgical properties and therefore does not harm performance characteristics. The scrap is preferred as the primary input over the virgin ore as a more cost-, resource-, and energy-efficient option.

Subject to factory type, steel supplied to the market for application in the construction sector can be with lower or higher recycled content, or sometimes virgin. Different production routes are also able to operate using different types of energy. Therefore, the project team was particular about checking the details of the materials before sourcing them, ensuring that it was recycled steel and not virgin steel.

This allowed the conclusion that project teams should contact steel producers directly to inquire about the specific production methods used to produce the structural steel. Although steel is almost always recycled, its carbon footprint may vary based on energy input (coal or gas-fired, grid electricity, renewable energy) and the fraction of scrap used. Table 3 illustrates the incorporation of recycled content into each considered building material:

One of the remarkable benefits of circularity is the carbon savings generated from recycled materials. Embracing circularity helps reduce emissions even in constrained conditions in terms of design and materials choice. Consecutively, Table 4 demonstrates the emission reductions achieved using building materials with higher recycled content.

Fig. 7 further depicts how carbon savings were made by using a low-carbon alternative to ready-mix concrete:

The information in Tables 3 and 4 and the graphical representation in Fig. 7 highlights the embodied carbon data per functional unit for three different grades of concrete that were used during the construction, in the two given scenarios (Business-*as*-usual and Actual). In the case of the Business-*as*-usual scenario, the project team used industry-average data for respective concrete grades, where no reduction measures were taken. The environmental impact profiles of industry-average materials are intended for use when no sourcing decisions have been made and no locally applicable generic profiles are available. They represent average materials for the performance criteria defined. All the data is derived from Ecoinvent, the database that contains more than 18,000 reliable life cycle inventory datasets, covering a range of sectors, and computed by OneClick LCA experts. Regarding the actual design, the team utilized the available EPDs and resorted to the industry-average data for those items that did not have EPDs. However, assurance letters provided by the suppliers guided the project team to select the right data from the materials inventory of the software.

7.3. Closing the loop and circular design

Circular design principles imply closing the loop by identifying the output of one system and connecting it to the input of the other. Simply put, turning waste into value, and minimizing the use of raw materials. Multiple strategies can help to achieve a lower embodied carbon footprint in projects. With the primary focus on the shell and core of a building, options could be used such as a reduction of materials quantities through lean design and more compact shapes and a reduction with the use of alternative building materials.

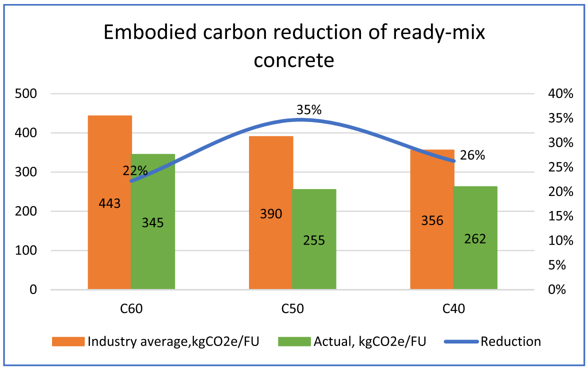

Fig. 7. Embodied carbon reduction of ready-mix concrete.

As discussed earlier, the climate in the UAE is harsh and dry, therefore, the project team had a limited choice of main building materials for all its structures. Weather and climatic conditions are important factors to be considered at the pre-planning stages since the wrong materials can lead to severe damage to the building in the long run and increase carbon emissions. The project team, in this case, was focusing on sourcing low-carbon building material, keeping in mind the climatic conditions of Dubai, as well as on the outcome of reducing embodied carbon throughout the supply chain and the construction phase. Extensive research and development exist in low-carbon building materials and products, and therefore, several options such as the use of by-products or recycled products are available in different countries.

One of the main examples could be green concrete, where the raw materials to form conventional concrete are substituted by byproducts of industrial processes and recycled materials and metals, as repeatedly recycled metals can still maintain their properties. The project team decided to use green concrete over regular concrete since it has higher strength and durability than traditional concrete. Not only does it harmonize with the natural environment, but it also reduces the need for excessive cement, thus reducing waste and GHG emissions which contributes to the circularity or closing of the loop [36].

8. Discussion

The circular economy presents a great opportunity for the built environment industry. To achieve the objective of highlighting the importance of LCA and its application in a real case in the construction industry, LCA was utilized in this case, as a technique to demonstrate the benefits of using it in the early stages of construction. The findings of this case have clearly shown that significant savings (26 %) in embodied carbon were gained because of using structural materials with a lower carbon footprint. This, in turn, was achieved because of the composition of materials such as green concrete and steel which had incorporated recycled substances and by-products, thereby reducing virgin content and eliminating energy needs for processing the latter. LCA at the pre-construction stage assisted the project team in identifying low-carbon materials and products, resulting in significant reductions in emissions and in closing some circularity loops. For example, confirming the safety and composition of recycled materials, clear communication, and collaboration among all the stakeholders as well as increasing the reuse rate of construction materials along with reducing waste are all principles of circularity that were demonstrated by the project team in the case of the construction of the G+2 SEE Institute building. A similar result by Charlotte et al. (2021) [66] highlighted that focus should be given to long functional-technical lifespan, longer use through adaptable design substituting high impacts materials with least impact biomaterials should be considered to improve the circularity aspect of any building along with multiple cycles. According to a report released by McKinsey, the transition to a circular economy in sectors such as mobility, food and the built environment alone could reduce carbon emissions by around 48 % by 2030 and 85 % by 2050 compared to the 2012 levels [67]. This suggests that if the construction industry is proactive, it can achieve these targets since there are solutions available that can help the planet recover to an extent. 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.

Application of LCA to support CE strategies could find a broader use if certain limitations were addressed and improved:

1. LCA only measures metrics that can be quantified, in the case of this study it was carbon emissions. Carbon emissions do not fully convey circularity. Impacts that are harder to understand, for instance, resource efficiency and environmental benefits of reusing timber for construction instead of sending it to landfill, are overlooked. There is no circularity indicator per se. The assessment could preferably investigate circularity performance on a scale of the entire building. This would give an idea of how to incorporate environmental sustainability aspects into the circular economy.
2. LCA is heavily dependent on the data collected by the professional conducting the analysis and the assumptions made in the process. Transparency of assumptions and reliability of data plays a key role in this assessment to avoid both over- and underestimation.

Conducting this study allowed the project team to explore the connections between the circular economy and embodied carbon reduction.

Keeping materials in circulation in the built environment is something that has not been properly addressed in most research to date, therefore, more effort is needed in this direction in future studies. Adoption of a circular design is a possibility with the reuse of materials, the use of materials with reclaimed content can certainly reduce the embodied carbon of the structure. Additionally, when climate conditions hinder design innovations or local policy instruments are not ready to support them, circularity seems to be a challenge in the reduction of carbon emissions. Therefore, the construction industry must take a new route to build products — circular, focusing on reuse and recovery, rather than harvesting, manufacturing, and delivering new materials, which is the linear way of thinking.

8.1. Practical implications

This research study demonstrates the significant impact the construction sector can make if careful consideration is given to the materials used during the construction phase. There is a need to get around the construction industry's various implementation barriers to the circular economy. One way would be for policymakers to enforce the use of recycled/salvaged materials to a certain extent. Another implication is the availability and reliability of data since if the data regarding materials is not accurate the developers will not be able to make accurate decisions and that will lead to poor results, in other words, project teams will not be able to demonstrate a real impact on reducing carbon emissions.

Using the circular economy practices should be considered when closing in on net zero carbon targets through embodied carbon reduction. With increased reuse and recycling, dependency on raw materials can be discouraged, resulting in lower emissions, before resorting to offsetting. Life cycle assessment as a tool at this stage does not evaluate the resource efficiency of the entire structure, nor does it analyze the circularity of the building at the end of the life stage. It does, however, include impact categories such as mineral resources/fossil resource use but does not go beyond materials. LCA conducted for buildings should expand its scope of impact, particularly including all the pillars of sustainability. A similar finding was reported by Saadé et al. (2022) [68] where the overall environmental performance of urban projects was tested. Finally, technology related to life cycle assessment needs to be developed in a way to provide better support to the engineers and project managers, who calculate embodied and operational carbon. It is important to mention that there is good software such as one-click LCA and others, however, most of them focus on products (materials) rather than on the building.

9. Conclusion and future outlook

In conclusion, the study successfully examined the interconnectedness between life cycle assessment (LCA) and the circular economy as well as the potential benefits of circularity to the construction industry. It was established that LCA is a valuable tool in reducing carbon emissions and supporting the transition to a circular built environment. The case study, a newly constructed G+2 multi-use building demonstrated significant carbon emission reductions of (26 %) achieved through proactive material selection and careful sourcing. Therefore, it is recommended that project teams should be proactive in selecting the right suppliers, who provide appropriate information about the source of the materials. Although conducting LCAs at multiple stages might be challenging and time-consuming, taking an informed approach can yield substantial benefits in the construction sector in the long run. It is important to develop a deeper understanding of the materials and the climatic condition of the specific area to help in slowing, narrowing, and closing loops, consequently, reducing waste and minimizing resource consumption originating from the construction sector. Though it may require additional investment in the short run, the long-term environmental and economic benefits make it valuable for the construction industry.

While it was recognized that life cycle assessment (LCA) is a practical tool for assessing various environmental impacts of products and systems, namely contribution to climate change, it still has a limited application in driving significant innovation within the field of the circular economy. This study, undoubtedly, could explore more verticals to support circularity in the built environment. For instance, integrating complementary methodologies such as Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) could have given a more comprehensive understanding of the building's overall sustainability and circular potential by including economic and social aspects in the analysis. This would have provided insights beyond the environmental impact and considered other important dimensions of circularity. Additionally, there was an opportunity to look at the design innovation and examine alternative materials that could mitigate the environmental impact across the entire life cycle of the building, going beyond its operational phase. This implies investigating new materials with improved recyclability or analyzing technologies that enable circular practices, such as modular construction techniques could be explored.

Besides, exploring strategies aimed at extending the product's lifespan through repair, refurbishment, or upcycling, all of which would ultimately diminish the need for frequent replacements of the building's components and foster circularity growth can be looked at in future studies. Involving analysis of emerging trends and technologies in the circular economy, such as digital innovations, sharing economy platforms, and advancements in waste management and their integration into the product's life cycle is a forward-looking approach to advancing circularity. Future studies can also focus on the importance of stakeholder engagement and collaboration throughout the value chain, including designers, manufacturers, consumers, and policymakers assisting to identify barriers and develop solid, actionable recommendations for a broader implementation of circular practices. Collectively, the identified scope of the study would have presented a more comprehensive approach to drive meaningful developments in circularity, providing a deeper understanding and feasible insights into this matter.

Ultimately, the study emphasizes the careful selection of materials, planning, and understanding of the climatic conditions while deciding on construction materials to promote a circular economy and reduce negative environmental impacts in the construction industry. By utilizing some of the recommendations discussed in this paper the construction sector can play a pivotal role in supporting the transition to a sustainable and circular built environment.

Author contribution statement

Jasmina Locke and Jacinta Dsilva: Conceived and designed the original draft; analyzed and interpreted the data; wrote the paper.
Saniya Z.: Performed the experiments; Contributed reagents, materials, analysis tools or data; wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

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

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