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Reducing the embodied carbon using bio-based building materials: the biogenic carbon content of timber

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Abstract. In recent decades, several efforts have been made towards the reduction of operational energy and therefore carbon, thanks to the introduction of mandatory compliance in many national regulations, achieved by using specific certification tools. As operational carbon diminishes, the significance of embodied carbon - emissions released before the building and infrastructure begins to be used - will continue to increase as a portion of total emissions.
Strategy for reducing embodied carbon include the use of building components derived from plants, which absorb atmospheric carbon during their growth through photosynthesis. Wood stands out among building materials, not only for its ability to store biogenic carbon but also for its lower emissions as per life-cycle assessments (LCA).
The purpose of this paper is to conduct an LCA of a wooden building using a Whole-Building Life Cycle Assessment (WBLCA) software, and to explore three methodologies for assessing biogenic carbon in LCA. It follows the two primary calculation methods provided by the EN 15804 and ISO 21930 standards for LCA, along with an additional "dynamic approach".
Key procedural discrepancies between the explored methodologies arise, guiding designers to adopt varying strategies in minimising a building's carbon footprint. This research aspires to underscore the shortcomings and advantages of prevalent methods.

Keywords: Life Cycle Assessment, biogenic carbon, timber, bio-based materials, dynamic LCA

1. Introduction

The achievement of targets outlined by the Intergovernmental Panel on Climate Change [1] in 2018 to restrict global warming to 1.5 degrees means for the building construction sector, being responsible for about 39% of the global greenhouse gas (GHG) emissions [2], to drastically reduce carbon emissions until reaching the net-zero status by 2050 [3].

In the last decades policies have primarily focused on the use phase, reducing the operational impacts of buildings by enhancing energy efficiency and increasing the use of renewable energy sources. Focusing on the use stage has also led to increased insulation thickness, better thermal performance in windows, and more efficient heat recovery systems. However, these improvements, coupled with the ongoing shift toward decarbonized energy sources, highlight that the emissions embedded in the materials used to build these new energy-efficient structures are becoming a more significant factor in a building's total life-cycle emissions [4].

To further reduce GHG emissions, the emphasis must now be pointed to address other stages of the building life cycle, including the embodied impacts from manufacturing, transport, construction, maintenance, and end-of-life processes. As operational carbon diminishes, in fact, the significance of embodied carbon will continue to increase as a portion of total emissions: the combined emissions from all building materials, products, and the construction processes used to assemble them constitute a building's embodied carbon. This represents approximately 20% of the total greenhouse gas emissions from the building sector.

Reducing embodied carbon is a practical strategy for mitigating environmental impacts in the construction sector; various approaches can be utilised to minimise embodied carbon, such as incorporating low-carbon, carbon-neutral, or materials with carbon-storing properties.

Low-carbon building materials are those with minimal embodied energy and carbon emissions throughout their production, assembly, and transportation. The manufacture and transport of construction products currently represents 23% of human-related GHG emissions [5], with over half of those as a result of cement and steel production, making its contribution to the climate crisis significant. Carbon-neutral and carbon-negative products are those which make use of by-products and recycled materials in substitution of some of their carbon-intensive traditional components: examples are the use of fly ash or granulated blast-furnace slag in place of cement. These terms have a broad definition, which can vary depending on context. For instance, metal products typically have high embodied carbon because their extraction and refining processes are carbon-intensive. However, if recycled metal products are used in new buildings, they can be seen as low-carbon. And the same goes for other materials such as glass and plastic.

The growing pressure to cut GHG emissions has driven experts to create low-carbon products that use bio-based materials. They can be effective allies in reducing the carbon embedded in building materials, thanks to their carbon sequestration properties. While growing, they absorb CO_2 through photosynthesis and store it, but release it back into the air as CO_2, CO, or CH4 when the biomass is transformed or decomposes through processes like combustion, digestion, composting, or landfilling.

Biogenic carbon can be defined as the capture and secure storage of carbon that would otherwise be emitted to, or remain, in the atmosphere. Bio-based products generally are able to sequester about 50% carbon by dry weight.

Different natural materials have been used in contemporary design practice. For instance bamboo products have gained significant attention recently because of the rapid growth, renewability, and widespread availability of this plant in both tropical and subtropical regions. Laminated bamboo is known for its exceptional toughness, outperforming even soft steel, and its surface is harder than red oak timber and fibreglass [6]. As a result, bamboo is frequently used in building structures, screen walls, and roofing components. Additionally, bamboo products have made their way into the recycled products building market, with treated bamboo flooring being a prime example.

Another natural material in which interest is growing as a viable substitute for construction elements is hemp, which, in forms of fibres, can be used to shape thermal insulation panels and wall-blocks; it also can take the place of part of the aggregates in concrete, in combination with lime and chemical binders, and be poured like the traditional one. One hectare of hemp can store up to 15 tons of carbon dioxide per year, effectively making this plant a carbon sink.

On a hypothetical scale for carbon sinking, wood stands out among building materials not only for its capacity to store carbon but also for its lower life-cycle emissions according to LCA. The carbon content in one cubic metre of wood, in fact, is roughly equivalent to that in about 350 litres of gasoline [7].

LCA of bio-based materials is a complex topic of ongoing debate; two central issues are whether biogenic carbon emissions should be included into LCA calculations and, if so, how to credit the duration that biogenic carbon is sequestered [8].

This study aims to analyse and understand the differences in the three most used methodological approaches to the assessment of biogenic carbon in timber, applying those to a mass timber case-study building, using a WBLCA software analysis. To explore the practical implications of incorporating temporal dynamics into environmental assessments of wooden buildings, this study uses both static and dynamic LCA approaches, aspiring to underscore the shortcomings and advantages of prevalent methods.

2. The biogenic carbon issue

The development of mass timber technology and related expertise in the last decades made it possible to build more and more mid- and high-rise buildings with wood and, as a consequence, many designers and builders view wood materials as sustainable substitutes for the traditional construction materials used for building structural frames, such as concrete and steel [9]. Thus avoiding the need for carbon-intensive manufacturing processes such as clinker production or steel smelting.

The carbon that wood has absorbed remains locked within the material, but a common concern is what happens to the timber when it reaches the end of its life. This is crucial for accurately accounting for biogenic carbon. When timber naturally decomposes, in fact, the stored carbon is released as gas. Although much of this is in the form of carbon dioxide, it's also known that if timber is left to decompose, it can emit methane. Methane's formation is significant because it can have a much stronger impact on climate change than carbon dioxide. Although methane typically remains in the atmosphere for only about 12 years, eventually oxidising into carbon dioxide, its Global Warming Potential (GWP) is far higher than that of carbon dioxide: over 20 years, it has GWP of 84 kg CO_2e, whilst over 100 years, it can have a GWP of 28 kg CO_2e.

2.1. *Timing of emissions*

An argument in favour of temporary carbon storage is that it buys time for climate mitigation efforts. Biogenic storage creates a delay in the release of carbon, which can temporarily lower atmospheric CO_2 levels, delay radiative forcing, and potentially help avoid certain climate "tipping points". This storage effect also "buys time" for the development of new climate mitigation technologies [8] while knowledge continues to advance. As a result, when the stored carbon is eventually re-released, its impact could be less severe than if it had been released today.

However, this delay in emissions might have a negative counterpart: by temporarily reducing atmospheric CO_2 levels, it could lead to a lower global CO_2 absorption rate. Consequently, when the stored carbon is re-emitted later, the reduced absorption rate could mean that overall atmospheric CO_2 concentration is higher at that point than it would have been without the storage delay. This temperature rise could increase the frequency of extreme weather events and the occurrence of certain heat-related illnesses [10].

In addition, an ongoing debate exists about when to recognize biogenic carbon sequestration for timber products. It could be marked either at the time of tree growth before harvesting or during the regrowth of trees that are replanted afterward. Moreover, the reference service life (RSL) of the building, which is often considered to be 50 years, is only half the rotation time period of the forest, considered to be 100 years.

2.2. *Accounting methods*

Two main methodologies are distinguished within the LCA literature regarding the biogenic carbon assessment during the whole life-cycle, based on how temporal biogenic carbon fixation and its release to the atmosphere are considered [9]. The first approach, currently most used by Environmental Product Declarations (EPDs), is the so-called “0/0” method, which considers neither sequestration at the beginning nor emission of biogenic carbon at the end-of-life; the second, indicated by most LCA regulations, is the "-1/+1" method and it accounts both for fixation of biogenic carbon during the A1-A3 phases (production stage) and for release in the C phase (end-of-life stage).

A third method, firstly introduced by Levasseur et al. [11] is represented by the so-called "dynamic approach", which accounts for the timing of emissions in LCA, using a dynamic inventory (detailing each emission through time) and dynamic characterization factors, with the aim of determining the impact of emissions for every time-step [10]. This methodology is gaining more widespread consensus, mainly because it addresses the significant shortcomings of other two approaches. In addition, this methodology also takes into account rotation time periods of the forest and the tree's typology, which are crucial parameters that are poorly considered in static approaches [5].

While static LCA assumes that all the elementary flows in a product's life cycle are emitted simultaneously, dynamic LCA assesses the environmental impacts across different time spans, according to both different moments of emissions and kinetics of their effects inside the ecosphere [12]. To better capture the impact of time, the dynamic approach makes use of time-dependent characterization factors and specific characterization factors that take into account the rotation period of biomass. Thus addressing the issue of timing of emissions: as a direct consequence, the moments of all the emissions must be known.

Recognizing sequestration in replanted trees, this approach accounts for varying growth rates, where faster-growing species absorb carbon more quickly compared to slower-growing ones. The longer the rotation period, the longer CO_2 remains in the atmosphere, leading to a higher biogenic GWP score.

3. Methodology

To evaluate the three methods for accounting for biogenic carbon content, a case-study building was used. The object chosen is a wooden building model that served as a scenario (among 20 different ones) for a research project (currently in press) conducted by two of the authors on the LCA methodology applied to several structural alternatives. The scenario was modelled by a team of engineers who proposed structural combinations, developed in conjunction with material-sciences experts and advisors collaborating with this project's researchers, and drawing from their feedback.

Although static and dynamic LCA differ fundamentally in their methodologies, the inventory modelling for both can rely on the same basic assumptions [13].

3.1. *Case study description*

The chosen building is eight stories tall, with spans measuring 6 by 3.5 metres and a floor-to-floor height of 3.5 metres (Figure 1), totaling a gross floor area of 5,376 square metres. The IPMS 4.2 standard for defining the usable floor area has been used as a reference for the GWP values, totalling 5,338 square metres. As the scope of the research was focused only on the superstructure, foundations and substructure, finishings, internal walls and systems are not included in the design. The construction is entirely made up of timber elements, excluding a reinforced concrete lateral-force-resisting core (which, by the way, was not considered in the research scope and, therefore, not reflected in the material quantities). Columns and beams are constructed using glued laminated timber (GLT) and the flooring system is represented by a five-layer cross-laminated timber (CLT) deck, topped with 6.4 cm of concrete reinforced by a welded wire mesh (Figure 2); the flooring system totals 23.9 cm in thickness.

Figure 1. 3D model of the case-study building

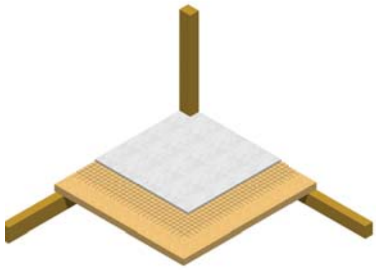

Figure 2. Sample of the structural node

The building, as designed by experts, has been modelled by means of using a Building Information Modelling (BIM) software (namely, Autodesk Revit was used), in order to have the opportunity to study in detail the building frames thanks to the accuracy improving of the structural elements, which have been designed using real geometric shapes for timber and, as a consequence of the presence of joints and connections, a more realistic and accurate amount of materials. The resulting bill of quantities is shown in Table 1, where discrepancies between the experts' modellation and the BIM model are also highlighted.

Table 1. Bill of quantities for the case-study building

Material	Type	Expert scenario volume (m^3)	BIM model volume (m^3)
Concrete, lightweight	2 1/2" (64mm) Concrete	341.73	346.95
Steel ASTM A992	Reinforcement bars	1.34	1.35
Lumber	5-ply CLT	938.78	953.98
Lumber	GL 12 1/4 x 13 1/2	107.52	104.05
Lumber	GL 14 1/4 x 15	130.06	126.58
Lumber	GL 12 1/4 x 18	163.92	154.86
Galvanised steel	Connectors	2.22	2.22

3.2. *Impact assessment methodology*

Thus, the LCA analysis will cover the A1-A5 and C1-C4 phases. Since the software datasets, like most available EPDs, provide aggregated information for the production stage, a single value is given for the A1-A3 phases (see Table 2).

Table 2. Building life-cycle stages covered by the study (adapted from EN 15879)

A1-A3	A4-A5	B1-B7	C1-C4	D

Product Stage	Construction Process Stage		Use Stage	End-of-Life Stage				Benefits and Loads beyond the system boundary
A1-A3	**A4**	**A5**	Not covered	**C1**	**C2**	**C3**	**C4**	Not covered

To assess the Life-Cycle impacts of the building, a WBLCA tool has been used, specifically One Click LCA (OCL). WBLCA softwares offer a much more straightforward approach to LCA, which is why they have become the standard tool for architects, engineers, and consultants conducting LCA on their designs. The software pulls information for inventory analysis directly from BIM, making it an intuitive and dynamic resource. It automatically uses material quantities to calculate environmental impacts by accessing an internal database that is based on EPDs or datasets frequently updated by the software company. Given that Paris, France, is set as the building site location, the parameters chosen for the LCA calculations via OCL are shown in Table 3.

Table 3. Selected parameters for LCA calculations via One Click LCA software

Parameter	Chosen value
Service life	Technical service life (same for the same material), which represents how long a type of material lasts in good condition
Material manufacturing localisation model	Enabled only for generic dataset: this adjust the material manufacturing process emissions for grid electricity and energy efficiency of the project location
Transportation distances	European model (typical defaults for each material) - km
End of life scenario	Incineration for wood, recycling for steel and concrete
Calculation tool	Life-cycle assessment for Level(s) - overarching assessment tool 7: Cradle to cradle Life Cycle Assessment - EN 15804+A2:2019

Since the focus of this study is on accounting for biogenic carbon content rather than the overall GWP value, average software datasets were used to assess each material from the Bill of Quantities. This helps avoid potential biases due to variations among different manufacturers when using EPDs.

The RSL of the building has been set at 50 years, which is customary, but it's important to note that this represents only half the rotation period of the forest, which is estimated to be 100 years.

4. Results and discussion

The LCA calculations run for the sample building totalled an overall GWP impact of 5.47E05 kg CO_2e, resulting in 102 kg CO_2e per square metre of usable floor area (baseline case). The production stage (A1-A3) amounts to 67.07 kg CO_2e/sqm, being slightly more than 65% of the total emissions. According to the software datasets the transportation phase (A4) accounts for only 2.49 kg CO_2e/sqm, while the construction stage totals 24.17 kg CO_2e/sqm and about 24% of the total. It's worth noting that the OCL software calculates the impacts from the construction phase by multiplying the gross floor area by the impact per square metre of a timber frame building. The end-of-life phase totals around 8.5% of the total, with the deconstruction process being the primary contributor with 5.47 kg CO_2e/sqm.

Research has shown that the key stages to monitor for determining the GWP impact of mineral-based materials are the extraction and production phases [5]. However, when bio-based materials and products are included in a building's LCA, focusing solely on the production phase can result in significant discrepancies from a comprehensive LCA. It is crucial to consider the end-of-life stage as well as the phase prior to extraction during biomass growth. Applying the “0/0” approach literally means disregarding both the amount and the flows of biogenic carbon throughout the life cycle of a building component made of timber. Regarding the case-study no biogenic carbon flow has been accounted for and the results are equal to those of the baseline (Figure 3).

This approach is considered relevant because it solves allocation issues related to biogenic carbon content [5]. However, this method does not connect the forest's rotation period with the building's RSL. This approach, while logical, can be seen as an overly simplified view of reality, ignoring potential benefits or drawbacks related to temporary carbon storage. Furthermore, CO_2 emissions at the end of a product's life might be less than the carbon initially sequestered. Assuming neutrality could

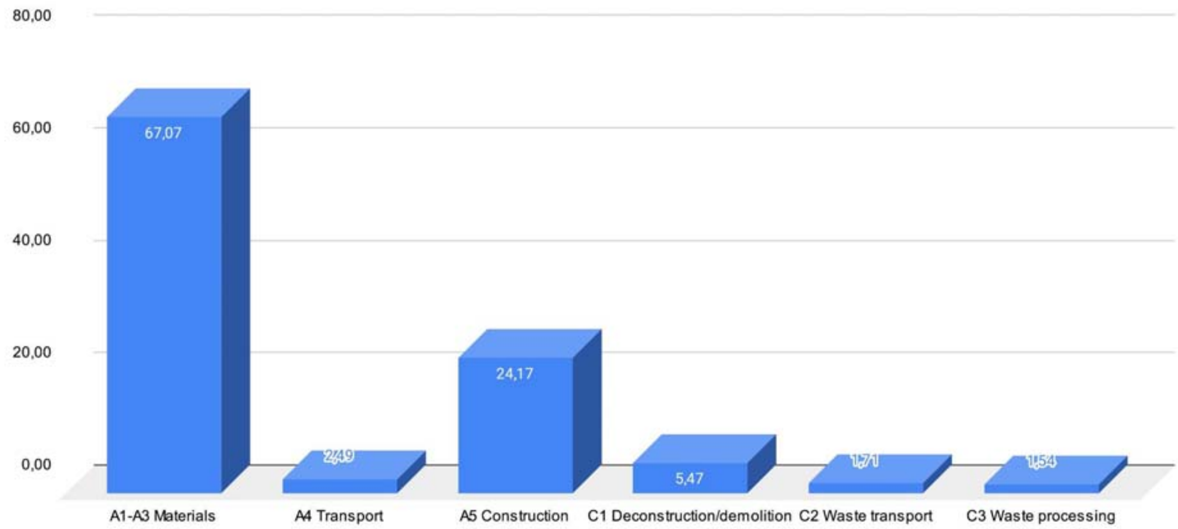

Figure 3. Life-cycle overall emissions by stage (kg CO_2e/sqm): baseline and “0/0” approach

therefore overestimate emissions and undermine the benefits of permanent storage. Additionally, the biogenic carbon stored in a timber product at harvest is just one part of a larger biogenic carbon system, which includes roots, soil, forest debris, processing waste, and unharvested trees [8]. This approach seems to be too much conservative and can lead to important errors in assessing LCA impacts.

In the “-1/+1” approach, as in the “0/0” approach, the overall impact totals the same as the baseline, which is 102 kg CO_2e/sqm. In this case, the impact of A1-A3 is -135.25 kg CO_2e/sqm, due to the biogenic carbon content of -202.32 kg CO_2e/sqm. Since the impacts for A4, A5, C1, and C2 are the same for both approaches, the waste processing phase (C3) calculated with the “-1/+1” approach totals 203.86 kg CO_2e/sqm, which is higher than the value obtained with the “0/0” approach. When applying the “-1/+1” approach, in fact, the total amount of biogenic carbon absorbed by timber during its growth is assumed to be completely released in the incineration end-of-life scenario, which is chosen for the baseline. In cases where timber elements are recycled or reused, even though the biogenic carbon is not emitted (except for the potential wood waste produced during deconstruction activities), it still gets transferred to another system, which, according to the standards, represents a biogenic carbon release (Figure 4). Under EN 15804, in fact, modules A-C adopt a so-called “cut-off” approach, which relies on the principle that the benefits of recycling should be attributed exclusively to the use of recycled materials in the initial production, while any potential benefits from recycling the product at the end of its life are disregarded (also called "100-0" approach).

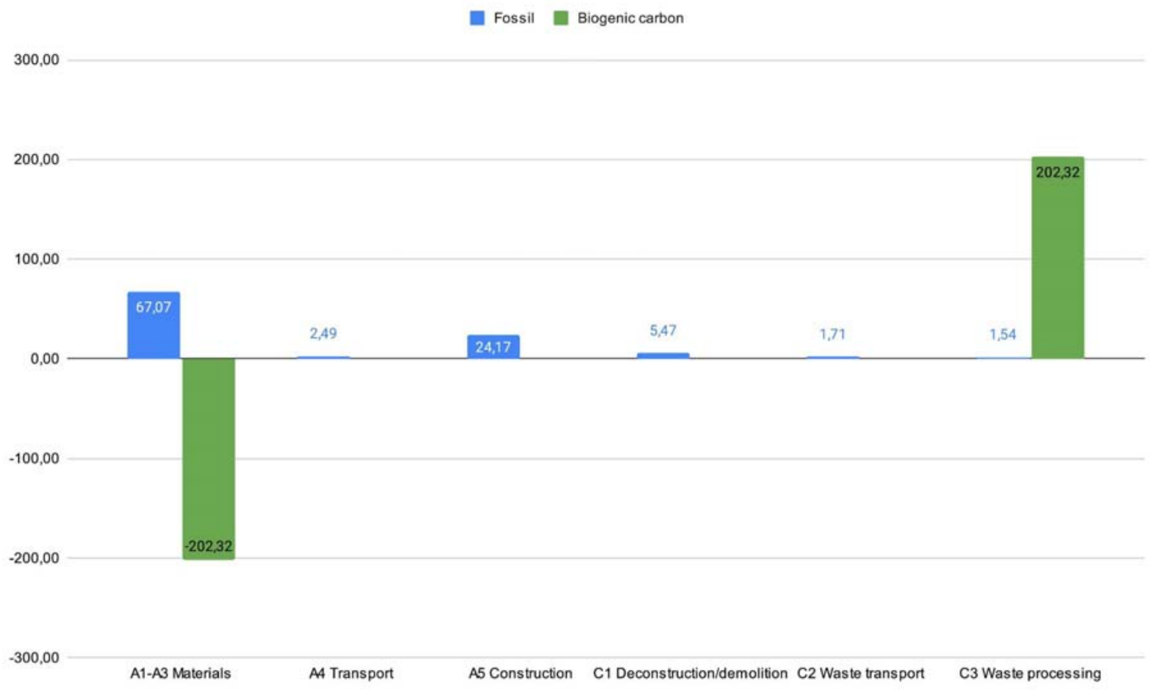

Figure 4. Life-cycle fossil and biogenic GWP impacts by stage (kg CO_2e/sqm). In the "-1/+1" approach, biogenic carbon enters the system in the A1-A3 stage as embedded content in timber, and it is completely released in the C1-C4 at the end-of-life

The biogenic carbon is also completely released for the landfilling scenario, this method assumes that landfills offer only a temporary sequestration of carbon. This assumption doesn't take into account that, under the newly updated IPCC guidance on solid waste disposal [14], wood is classified as a "less decomposable waste". This classification, based on studies of typical decomposition patterns, assigns wood a DOCf (degradable organic carbon fraction) value of 0.1. Consequently, in landfill scenarios, it's assumed that 10% of the organic carbon content decomposes and is released into the atmosphere, while the remaining 90% is effectively considered permanently sequestered. This natural decomposition process can have potentially negative impacts, but these are usually avoidable in practice. Landfill sites containing organic material often have systems in place to capture the biogas produced during decomposition. This not only prevents methane from escaping into the atmosphere but also allows it to be used as a fuel source or for other applications. Although this approach isn't implemented universally, it shows great potential to reduce decomposition-related emissions, especially since not all methane emissions are currently captured. To address this potential inconsistency, a "-1/+1*" variation has been proposed [9]. In this approach, landfills and recycling are considered as partial permanent sequestration of biogenic carbon, resulting in fewer emissions being accounted for in the end-of-life stage and giving a more realistic picture of biogenic carbon fluxes.

Among the many standards, also the EN 15804+A2 [15] recommends using the "-1/+1" approach, where the benefit (-1) is accounted for at the initial stage of the life cycle and the burden (+1) is taken at the end of the life cycle. The environmental impact of the production stage for bio-based materials is often reported as a negative value, as their EPDs typically cover only the A1-A3 phases. These negative values can encourage LCA practitioners, architects, and developers to incorporate these materials into their buildings. However, this information can be misleading because the overall impact of these components is not necessarily negative, and it greatly depends on the end-of-life scenario. According to the cited European standard, EPDs of construction products shall address at least both the production stage (A1-A3) and the end-of-life stage (C1-C4), with module D (benefits and loads beyond the system boundary) being separate and not mandatory. Waiting for other standards to harmonise, it is crucial not to limit the assessment to the product stage to use this approach and ensure a comprehensive evaluation.

In addition, the "−1/+1" approach is based on the fundamental assumption that timber (and generally the biomass) used in buildings comes from sustainably managed forests with continuous rotation and a constant level of carbon in the forest carbon sinks so that it can be considered carbon-neutral. This provision is requested by both EN 15804 and ISO 21930.

The combustion of biomass produces more GHG emissions per unit of energy compared to burning fossil fuels. This "carbon debt" is gradually repaid if new biomass grows and captures carbon from the atmosphere. The capture and release of biogenic carbon is a cyclical process, unlike the one-way emissions resulting from burning fossil fuels [8]. However, the time it takes for this biomass to grow back can have significant climate impacts, particularly when it involves wood, since forests can take decades to fully mature and sequester the extra carbon released during combustion.

For timber, where carbon sequestration takes place incrementally over time, both these static approaches might not accurately capture the temporal dynamics of biogenic carbon sequestration in regrowing forests [13]. To achieve this, the application of a dynamic approach is suitable, involving the use of dynamic characterization factors for the global warming impact category. Results of this approach thus express the time-dependent radiative forcing caused by the GHG life cycle emissions over a time period from the emission date to a selected time horizon. Dynamic LCA assesses every GHG consistently using its specific radiative forcing time-dependent curve [10]. This approach makes it possible to understand how sensitive the results are to the choice of a time horizon, as it's not predetermined at the outset of the study. For this purpose, a spreadsheet [16] has been used to calculate the carbon decay, combined with the integrated radiative force, over the set time horizon of 100 years.

The calculation process for the biogenic carbon content assessed through the dynamic approach is still ongoing as we write this. However, some preliminary findings are available, and a general trend is identifiable, highlighting the influence of the time variable on the evolution of biogenic carbon uptake's effects over time [5]. It is crucial to determine when biogenic carbon uptake begins, whether it starts before or after building construction. In the first case, in fact, the amount of biogenic carbon is significantly larger than in the latter. If the forest is regrown at the end of the building's life, then carbon neutrality could be achieved [5]. Discount rates are also proposed in order to take into account the progressive decay of carbon presence in mass and consequent radiative forcing [11].

Considering biogenic carbon uptake after construction is preferable from a sustainability perspective, as it encourages future forest regrowth. However, for the case study, because of the long timeframe required for forest regrowth, only a portion of the CO_2e stored in the building is recaptured by the forest. This leads to lower biogenic carbon uptakes and higher GWP values compared to the "-1/+1" approach, which accounts for all carbon flows at the time they occur.

5. Conclusions

The increasing use of timber elements in building construction is giving rise to the biogenic carbon and the accounting issue related to it. Moreover, the assessment of biogenic carbon is expected to increase as future buildings will continue to reduce their operational GHG [5]. Regrettably, there is currently no consensus regarding how to treat biogenic CO_2 in LCA. In this article we showed that not considering biogenic CO_2, e.g. adopting the "0/0" approach, can lead to biased conclusions. If a fraction of the biogenic carbon is assumed to be sequestered permanently, as for the landfill scenario, then the amount of biogenic carbon entering the product system is not equal to the amount leaving the system, which means that biogenic CO_2 emissions cannot be considered neutral [10]. Although it was previously thought that wood was a significant source of methane emissions from landfills, recent studies have shown that food waste can disproportionately contribute to methane emissions. Landfill might be a better option than energy recovery, despite being banned or constrained in some legislations [17].

Also, as soon as a benefit is given for temporarily storing carbon, even if the total amount of biogenic carbon entering the product system is equal to the amount leaving the system, then it becomes important to account for the timing of every CO_2 flow that occurs in the life cycle inventory [10]. The timing issue also compromises the accuracy of the "-1/+1" approach in accounting for biogenic carbon. The dynamic approach, therefore, appears to be the most effective method for accounting for biogenic carbon. However, the time horizon remains a point of debate, as it does not appear to fully comply with LCA principles, which stipulate a consistent time horizon for all substances and emission events [12].

Key procedural discrepancies between the explored methodologies arise, guiding designers to adopt varying strategies in minimising a building's carbon footprint.

Although there are many scientific arguments for incorporating temporal factors in LCA, it's crucial to recognize how this fundamentally different approach to emissions accounting could affect design incentives for practitioners. This impact is often overlooked in the current literature [15]. Furthermore, any GHG emitted at any point, even hundreds of years from now, will definitely have an impact as it follows a degradation kinetic, leading to an inevitable effect [12].

Timber is unquestionably a sustainable building material. When combined with sustainable forestry practices, wood-based construction can turn cities into carbon sinks, supplementing the carbon sequestration provided by forests [4]. An efficient way of using wood sources is its plantation before usage. This will create advantages like carbon sequestration, water retention, and biodiversity conservation beside the wood production. Compared to natural forests, intensively managed planted forests can produce up to 2 and 25 times more wood biomass per hectare [4].

Buildings can offer extended carbon storage, particularly in urban regions where real estate demand is rising. This rising need can prevent older wooden buildings from becoming outdated, thus increasing the biogenic carbon urban sinks [4]. The extension of carbon storage cycles for wooden products, focusing on the reuse and recycling of wood and timber structures, requires further research. Longer wood life cycles contribute to increased carbon storage on a global scale [18].

Besides the use of carbon-negative materials and revitalising existing buildings, embodied carbon can be reduced by choosing low-carbon construction materials and/or reusing building components. Other strategies include extending their service life, minimising usable areas, and optimising buildings and their components. With thoughtful design, it's possible to build structures with low embodied carbon at little or no additional cost, potentially even yielding economic benefits [19].

Author Contributions: Conceptualization, EG, GP and DT; methodology, EG, GP and DT.; formal analysis GP; writing-original draft preparation GP; writing-review and editing GP; supervision EG and DT. All authors have read and agreed to the published version of the manuscript.

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Peer Review Statement

All papers published in this volume have been reviewed through processes administered by the Editors. Reviews were conducted by expert referees to the professional and scientific standards expected of a proceedings journal published by IOP Publishing.

- **Type of peer review:** Double Anonymous
- **Conference submission management system:** Morressier
- **Number of submissions received:** 112
- **Number of submissions sent for review:** 97
- **Number of submissions accepted:** 69
- **Acceptance Rate (Submissions Accepted / Submissions Received × 100):** 61.6
- **Average number of reviews per paper:** 2
- **Total number of reviewers involved:** 33
- **Contact person for queries:**
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Preface

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PREFACE

This **NEXTBUILT 2024** Conference Proceedings comprise the selected papers contributing to the 2024 **International Conference on Challenges for the NEXT generation BUILT Environment**, held in Bologna on two years basis, with the ambition to become a reference event to share and discuss drivers of change, barriers and solutions for shaping the future built environment considering the impact of Climate Change. The Conference is one of the main outcomes of the NEXTBUILT Observatory, whose main scope is to collect, analyse, and report information, research, and studies dealing with the most urgent and hot topics influencing the transformation directions in contemporary cities with a forward-looking perspective. The initiative is supported and fed by the research activity run at the Department of Architecture of the **University of Bologna** as well as by the constant transformative plans led by the City of Bologna.

NEXTBUILT 2024 was **held in Bologna on May 9th and 10th 2024**, with the chance to join the conference online for those who were not able to attend in person, under the overarching theme of **"a reflection on the future of the built environment within a context of resource scarcity or heavily influenced by climate change impacts, assuming a strong future oriented approach"**.

The conference was accordingly organized around four main topics:

- **Energy use and affordability in the built environment**
  Energy market global instability, progressive fossil fuel scarcity and related price fluctuations call for new approaches which combine technical and socio-economical interventions to possibly ensure fair and sustainable access to adequate energy services for all. Nonetheless, energy poverty rates are rising globally without effective and future-oriented solutions being promptly drafted to mitigate the impact of this issue. Besides, it strongly emerges the need to shift to cleaner energy sources while possibly reducing the demand intensity and impacts of the building sector. It is largely agreed within the scientific community that structural changes should be made to reduce the roots of energy challenges in the built environment, but how can policymakers, planners, and designers innovate the retrofitting market remains an open issue despite it is acknowledged to be the most urgent and promising field of action.
- **Water scarcity and cities response capacity to extreme events**
  In recent years, many countries worldwide have suffered the effects of climate change, especially in relation to water. From devastating floods to severe droughts, water scarcity or abundance is increasingly affecting life in urban environments, involving over half of the world population according to IPCC projections. On the one hand, conventional water management solutions in cities have been proven inadequate to address intense rain events and water needs; on the other, progressive climate topicalization is posing a risk to ensuring adequate access to fresh water. Cities are actively seeking effective solutions to reduce the flood risk and save water for use (including, among others, water-efficient buildings and construction processes), but more integrated and interdisciplinary approaches are not well-established yet. More integrated and systemic solutions to let cities and buildings be reshaped to mitigate and/or adapt to increasingly severe water-related issues are needed.
- **New paradigms in buildings and components expected lifetime**
  Heavy depletion of natural resources and the need to achieve carbon neutrality targets are strongly encouraging policymakers, researchers, and designers to change their perspectives on life-cycle impacts, durability and service life of buildings and components. However, the majority of current interventions in the building sector are still focused on lowering the operational energy demand while paying less attention to embodied energy and carbon as well as to the end-of-life stage. The increasingly fast evolution of needs and requirements is calling to strategically rethink the expected lifespan of buildings and to carefully consider the use of materials and design choices within a circular-based perspective, not only at the local level but also at a larger scale. This seeks for innovative measures, methodologies, procedures, and tools to facilitate and support a mind shift and a market transition.
- **Tools and means to go beyond the climate neutral transition**
  Current policies, measures and tools to achieve sustainable development and carbon neutrality have largely proven inadequate and limited. Many of them can only deal with short-term visions and effects of planning procedures, design, and building processes. However, given the unpredictability of the future in the long run, effective and forward-thinking measures must be taken now. Can the carbon neutrality challenge, which is now assumed to be a target, be turned into a useful means to that end?

The main issue remains to plan, design, and build for future changes that will almost certainly imply progressive resource scarcity (physical and non-physical) along with other challenges yet to come.

The breadth and urgency of the topics allowed to collect several insightful and novel contributions spanning current trends and innovations, empirical findings and concrete applications in the fields of science, industry, policy, and governance. However, the main detected barriers to concrete progress deal with the lack of systemic approaches and long-term visions to go beyond the urgency of the present time. In the background, the need for more balanced and environmentally driven economic models remains a turning point yet to come.

The conference stimulated a vivid dialogue between the invited keynote speakers and the participants in both the plenary and parallel sessions. NEXTBUILT 2024 had the privilege to host:

- **Brenda Boardman**, from the Environmental Change Institute, University of Oxford, whose studies since the early 90s contributed to providing the definition of Energy Poverty still in use globally. Her key lecture titled ***Energy prices, energy efficiency and equity*** considered the competing needs of the poorest households and climate change, both today and into the future.
- **Louisa Bowles**, Partner and Head of Sustainability at Hawkins\Brown, who has led several multi-disciplinary projects and is an active contributor to many industry organisations working to improve environmental performance. Her key lecture titled ***Circular economy, buildings as material banks*** stimulated a reflection on a mind shift in the way we use and understand the service life of materials in contemporary architecture.
- **Paolo Negro**, Research officer at the Joint Research Centre of the European Commission, with a long experience in research activity and scientific policy advising, whose key lecture titled ***A strategy for the holistic rehabilitation of buildings and the new European Bauhaus*** outlined the main challenges at EU level with reference to multiple actions under the umbrella of the green deal.
- **Elisabete Teixeira**, from the University of Minho where she serves as a dedicated Researcher at ISISE (Institute for Sustainability and Innovation in Structural Engineering). Her key lecture titled ***Synergizing nature-based solutions for water resilience and urban infrastructure protection*** highlighted the importance of more coordinated actions and systemic approaches to put in place more effective mitigative strategies.

The conference included eleven parallel sessions organised during the two days to expand the dialogue opportunities and to let all the participants from seventeen countries exchange ideas and proposals for facilitating synergies and future cooperation opportunities. A NEXT TALK inviting three architectural design firms, NET Engineering, Pier Currà Architettura, Open Project, was also held to bridge the gap between academic research and the professional market enlarging the horizon of research to very practical implications. As the necessary transition of our built and urban environments is becoming more urgent NEXT BUILT tried to attract the attention of the key involved stakeholders to stimulate collaboration and partnerships while laying the foundations for meaningfully shaping policy, practice, and capacity-building programs.

This Proceedings collect the main individual contributions organized according to the four main topics that underpin the conference's scientific program. Each submission underwent a two-round (abstract and full paper) double-blind peer-review process. The NEXTBUILT Scientific Committee and the Editors carefully handled the process to ensure only those meeting the necessary scientific standards were presented at the conference and included in these
proceedings.

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8 July 2024

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