Master Thesis by Joas Vandiest

Decision-making framework for biogenic carbon accounting methods – a case study impact evaluation of temporal considerations in LCA

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Thesis Research Project

Title

Decision-making framework for biogenic carbon accounting methods – a case study impact evaluation of temporal considerations in LCA

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Abstract

The building sector's contribution to global CO_2 emissions requires innovative approaches to reduce its environmental impact. Mass timber offers a viable solution due to its lower global warming potential during production and its ability to temporarily store carbon. This storage not only reduces radiative forcing, but also removes carbon from the atmosphere and can help mitigate climate change. The inclusion of biogenic carbon flows in LCA is therefore essential to accurately assess the environmental performance of a mass timber building. However, European standards do not include this in their guidelines for conducting LCA of bio-based materials. A systematic review of LCA studies on mass timber buildings highlighted the low presence of biogenic carbon flows and found the need for an advisory decision tree framework for accounting for these flows. Through an applied case study of a recent mass timber building project in Rotterdam, this research itself demonstrated that prolonged storage periods of wood products in construction can lead to a negative Global Warming Potential (GWP) score, thus supporting the inclusion of biogenic carbon in LCA models. However, the variability of LCA methodologies makes it difficult to compare studies on bio-based materials. To address this, a harmonization process among standardization organizations is recommended. Therefore, the decision tree framework is intended as a first approach to guide practitioners on how to model biogenic carbon, emphasizing the importance of accounting for temporal storage and forest dynamics based on a GWP-bio value.

Keywords: built environment, global warming, bio-based materials, mass timber, biogenic carbon, Life Cycle Assessment (LCA),

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List of Abbreviations

Abbreviation	**Definition**
CEN	Comité Européen de Normalisation
CF	Characterization factor
CH_4	Methane
CLT	Cross Laminated Timber
CO_2	Carbon Dioxide
EN	European Norm
EoL	End of Life
EPD	Environmental Product Declaration
EU	European Union
GHG	Greenhouse Gas Emissions
GLT	Glued Laminated Timber
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MPG	Milieuprestatie Gebouwen
PCR	Product Category Rules
RF	Radiative Forcing
RSL	Reference service life

1. Introduction

1.1. Wood as a building material

Emissions from the global construction industry are one of the most pressing issues facing society today, with the use and construction of our built environment accounting for 39% of the global process and energy-related CO_2 emissions (Crawford, 2022). Concrete and steel are responsible for a large proportion of these emissions, which are caused by the production, manufacture, processing and transportation of these materials (Amiri et al., 2020). Mass timber, the umbrella term for engineered wood products, has been repeatedly cited as an innovative building material to address the high number of emissions in the construction sector (Heräjärvi, 2019; Kriegh et al., 2021). First, it is a renewable resource that is not extracted from the already scarce natural resources. In addition, its processing and application offer significant environmental benefits compared to the production and application of steel and concrete. Comparative environmental assessments of mass timber structures have shown that the bio-based material has a lower impact on climate change than concrete (Allan & Phillips, 2021; Chen et al., 2022).

Mass timber used in construction consists of large structural components made of smaller boards laminated together, such as cross-laminated timber (CLT) and glued laminated timber (GLT), also known as glulam (Chen et al., 2022). Particularly the former is the type of mass timber that is responsible for the recent rise in popularity of wood construction. In addition to being a rather durable and environmentally friendly product, wood is even more fire resistant than its concrete and steel competitors due to its structural strength and longer burning time (Buchanan & Östman, 2022). Because the material is lightweight yet mechanically strong, this type of mass timber can be easily assembled and dissembled into modules and prefabricated off-site (Kwok et al., 2020). Using this modular building technology, construction phase changes do not require extensive preparation, saving both time and money, while also providing higher-quality end-of-life (EoL) options. In terms of in-use benefits, mass timber has a relatively high thermal conductivity and can improve a building’s indoor air quality (Craig et al., 2021). CLT and glulam have been used in many large construction projects around the world, including the Netherlands. An example of a new Dutch construction project is “SAWA” in Rotterdam, which will be the country's first 50-meter residential building to be constructed largely of CLT and glulam (Welch, 2023).

In addition to these many benefits for the construction industry, the main reason wood is being considered as a potential replacement for concrete and steel is its ability to absorb and store carbon during its lifetime (Churkina et al., 2020). This form of carbon is called biogenic carbon and refers to the carbon that is captured from the atmosphere as CO_2 in the process of photosynthesis during biomass growth in plants, trees and other forms of biomass (Hoxha et al., 2020). Churkina et al. (2020) argue that this type of carbon storage in buildings is safer than, for example, pumping CO_2 underground and could therefore become a viable solution for reducing emissions in the construction industry. Cementitious materials (e.g. concrete) also have the ability to store carbon, which is done through the carbonization of hydration products (Pomponi et al., 2020). However, the amount of carbon stored is only a fraction of the carbon that is emitted during the manufacturing process, so the material is still a net carbon emitter. Together, these reasons have led to the wide adoption of mass timber in many construction projects, and when combined with concrete cores, it is considered possible to use the material to build our future skyscrapers (Kuilen et al., 2011).

To investigate the environmental impacts of mass timber and to assess whether it is indeed more beneficial to use it in the construction of our buildings, conducting a life cycle assessment (LCA) is internationally recognized as an appropriate method (Klöpffer & Grahl, 2014). It is capable of quantifying a wide range of environmental impacts of building materials and products, such as global warming potential and marine ecotoxicity. LCA focuses on the material and energy flows associated with a building throughout its life cycle, from the extraction of raw materials for the production of building materials, through the use of the building, to the decommissioning of the building and the final disposal and recycling of building materials (Säynäjoki et al., 2017). They are often used to compare, for example, CLT with a non-bio-based product (Chen et al., 2022) and aim to determine which material performs better in the various environmental impact categories. However, as bio-based materials have several points of contention that are difficult to agree on between different researchers, this is in reality quite difficult (F. Morris et al., 2021). One of the main differences is the treatment of biogenic carbon emissions, specifically the timing of these emissions and the modeler’s EoL choices. The approach and assumptions made by the practitioner can have affect the final results of the assessments due to the regenerative and storage capabilities of wood (F. Morris et al., 2021).

For this complex issue, it is important to understand the nature and timing of biogenic carbon flows through the life cycle of the material, as shown in Figure 1 (WoodWorks, n.d.). The process begins with the growth of a plant, which results in the sequestration of biogenic carbon in its tissues. Once the wood is harvested from the tree, the logging debris is either left in the forest to decay or burned for bioenergy, producing emissions known as biogenic CO_2 and CH_4 (methane). At the mass timber manufacturing facility, waste from the manufacturing process is similarly burned, producing biogenic carbon emissions. The actual building product, CLT beams, will retain the sequestered carbon during its use in the construction (Kwok et al., 2020). Bio-based materials such as wood are known to retain up to 50% of this carbon on a dry mass basis. Depending on the EoL scenario, some form of degradation of the biomass (e.g. incineration or combustion) will release the carbon back into the air as CO_2 or CH_4 (Hoxha et al., 2020). When the product is decomposed in landfill, a fraction of the biogenic carbon can be stored indefinitely. All this together results in the balance of biogenic carbon always to be equal to zero or negative in the case of permanent storage (WoodWorks, n.d.).

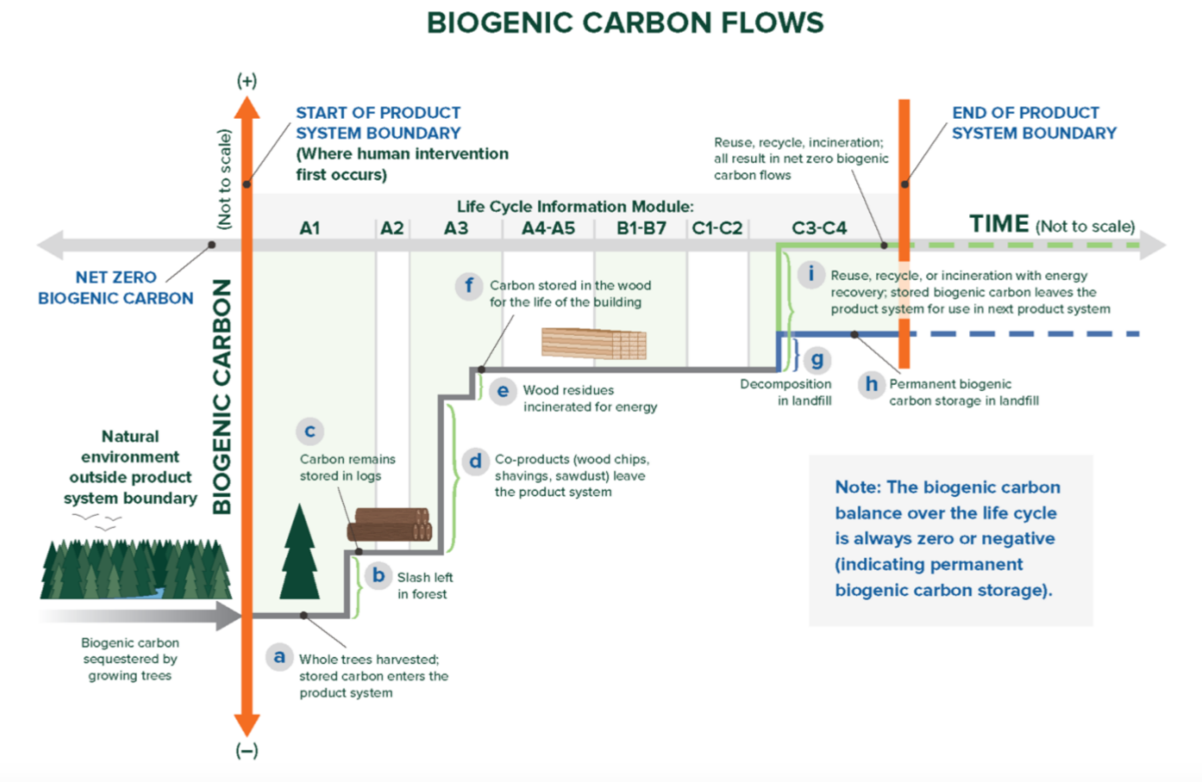


Figure 1: Visual overview of mass timber life cycle stages per ISO 21930 (ISO, 2017), reported on the WoodWorks website (WoodWorks, n.d.).

1.2. Biogenic carbon accounting in LCA

1.2.1. Carbon neutrality

Hoxha and colleagues (2020) have highlighted the commonly used biogenic carbon accounting methods, often referred to as the 0/0 and -1/+1 approaches. These follow the carbon neutrality principle which states that in a sustainably managed forest system, there is a balance between the release of carbon at the end of its life and the input of carbon into the product system The reasoning behind this is that the biogenic carbon undergoes a relatively short carbon cycle and is therefore not expected to have a significant impact on the climate in the long term (J. H. Andersen et al., 2022).

The 0/0 approach essentially means that biogenic carbon flows are equal to 0 for the characterization factors (CFs) of the GWP impact category (Hoxha et al., 2020). In Figure 2, this is visualized as the black arrows showing only the fossil-based emissions. The biogenic carbon flow associated with the uptake prior to the construction is set to 0, similar to the equivalent release at the end of its life when the product is incinerated. While the 0/0 approach sets the biogenic carbon CFs to 0, the -1/+1 approach uses a CF of -1 for the uptake and 1 for release of biogenic carbon, additionally providing an overview of the flows in the affected modules of a building’s life cycle. This is also shown in Figure 2 as green arrows, where the transfers between the different systems (forest, building, potential subsequent product) are also included. It is important to note that this neutrality refers to the biogenic carbon emitted as CO_2; if the biogenic carbon uptake is instead emitted as CH4 instead, the biogenic GWP results in each individual life cycle stage will not equal zero (Hoxha et al., 2020).

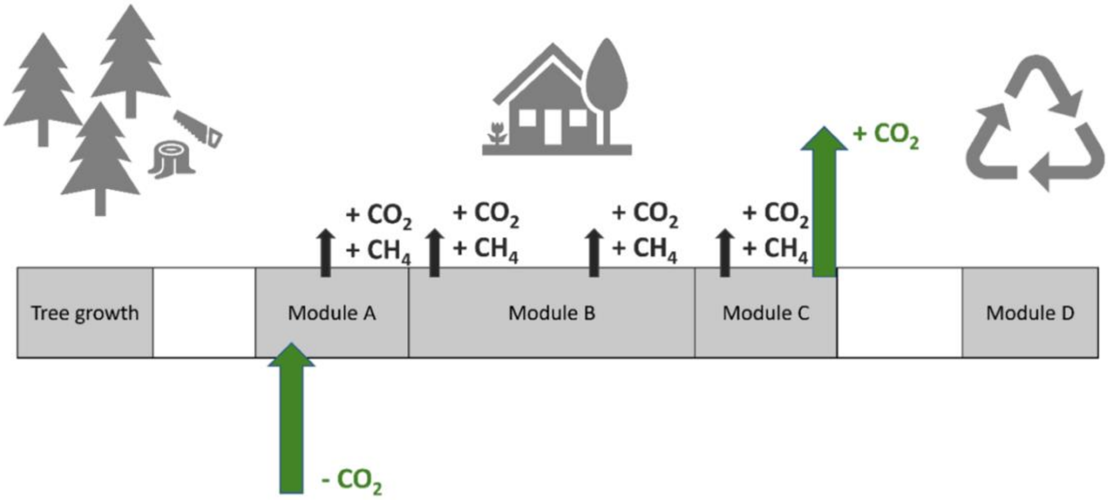


Figure 2: Visualization showing the differences between the 0/0 approach and -1/+1 approach. While the 0/0 approach only considers the black arrows (fossil-based emissions), the -1/+1 approach additionally includes the green arrows (biogenic carbon emissions) (van den Berg, 2023, p. 14).

In cases where the carbon neutrality assumption is applied, the final carbon emissions of the product and construction process stages are often found to be lower, but at the same time higher in the EoL stages (Hoxha et al., 2020). Since the system boundaries of LCA studies vary quite regularly between certain life stages and modules (i.e., cradle-to-gate or cradle-to-site), this could lead to unwanted differences in the results. Thus, while the presence of the biogenic carbon seems to be an advantage over the first approach, the carbon balance over the whole life cycle is still zero and could lead to misleading results if the modules are evaluated individually. A previous study therefore preferred the 0/0 approach to the -1/+1 approach, as it essentially neutralizes the aforementioned allocation issues with respect to biogenic carbon (Frischknecht, 2010).

1.2.2. Timing of emissions

The common way of treating the biogenic carbon emissions in LCA can be a controversial issue, where several groups of researchers have questioned the current methodology and the corresponding carbon neutrality principle (Brandão et al., 2013). This is mainly due to the idea that these two approaches do not consider the aspect of the temporal complexity of the material. The temporary storage of carbon in wooden building materials reduces radiative forcing of CO_2, which provides more time for technological innovation and has a significant impact on reducing the risk of exceeding short-term environmental tipping points (Brandão et al., 2013). Due to the temporal nature of the material and the consequential complications, it is essential that environmental assessments of bio-based products are conducted in a transparent and universal manner

A new approach, unlike the previous two, incorporates the temporal aspect with Levasseur et al. (2010) being the one that introduced dynamic emissions instead of using a single number. As argued in the dynamic method, it can be of great importance to determine the time period in which the forest carbon sequestration takes place can be of high importance. In order to do this, the Life Cycle Inventory (LCI) of the bio-based material must include both the GHG emissions and the sequestered carbon to specify in which year they occur. Therefore, such a dynamic LCA includes the forest in its system boundaries (Levasseur et al., 2010). There are essentially two scenarios in which the dynamic biogenic approach can be modeled, both shown in Figures 3 and 4 (Hoxha et al., 2020). The first scenario of this dynamic LCA considers the carbon sequestration of the forest before the harvest of the product, also called the ***growth*** scenario. This scenario follows the natural carbon cycle in real life, where the biomass of the wood first has to grow before it can be harvested. The second scenario is known as the ***regrowth*** scenario, which considers the same number of trees to be replanted immediately after harvest when the life cycle of that specific wood product begins (Levasseur et al., 2010; Peñaloza et al., 2016).

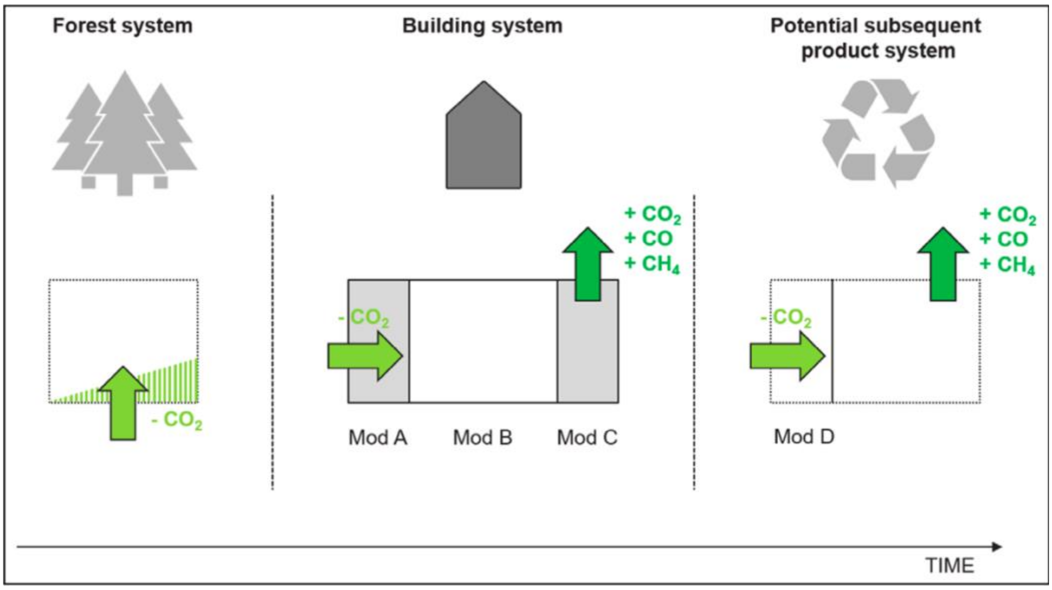


Figure 3: Dynamic approach, *growth* scenario. The flows in light green represent carbon uptake, while the darker green stands for its consequent release (Hoxha et al., 2020, p. 507).

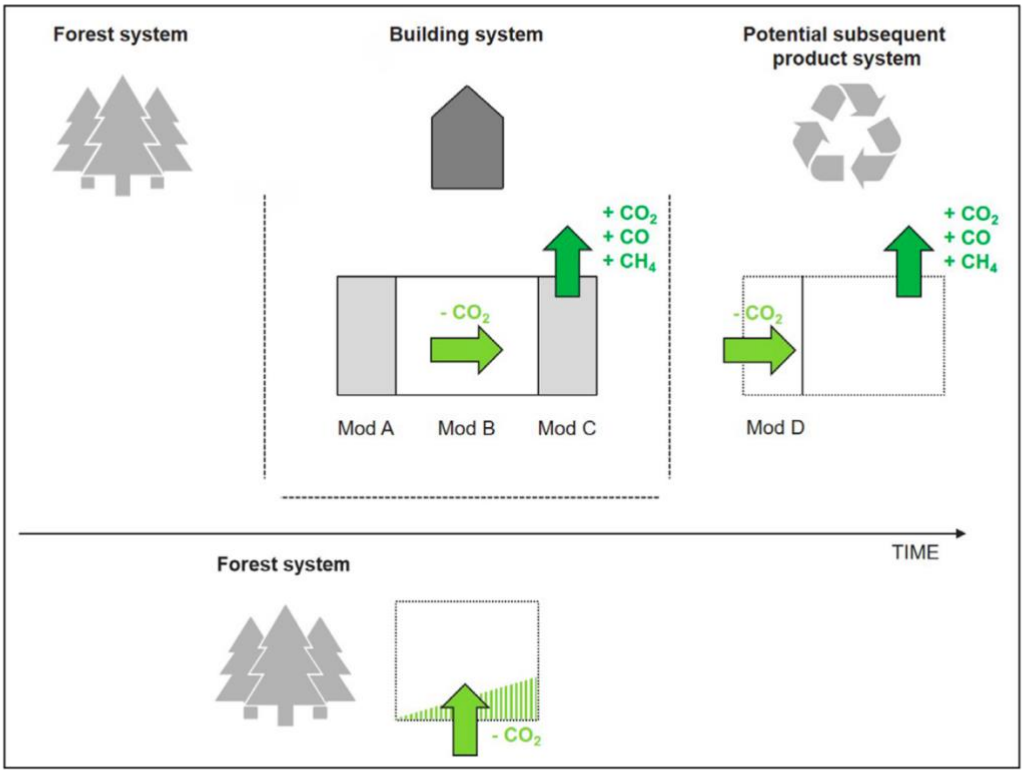


Figure 4: Dynamic approach, *regrowth* scenario. The flows in light green represent carbon uptake, while the darker green stands for its consequent release (Hoxha et al., 2020, p. 507).

As the importance of this timing was highlighted in their previous study, the authors of the article decided to test their assumptions by studying a wooden chair (Levasseur et al., 2013). This article showed that the carbon neutrality principle does not hold, while not accounting for biogenic carbon emissions can lead to misleading results and therefore biased conclusions. In addition, since such a significant difference was found between the two scenarios, the authors gave their recommendation on which scenario should be used for what purpose. The *growth* scenario can be used in a situation where the trees are planted specifically for the construction of a wood product, such as for afforestation purposes. The *regrowth* scenario is useful in a situation with a sustainably managed forest, because it assumes that the forest provided a tree that can be used as a raw material and since wood is renewable, it can be replanted (Levasseur et al., 2013).

Following the introduction of this new approach by Levasseur et al. (2010), several studies have investigated the concept of temporality with respect to biogenic carbon and its influence on the LCA methodology. Fouquet et al. (2015) found a positive effect on carbon sequestration and significant variations within the different scenarios. Dynamic LCA was found to provide a more informed analysis of emissions and radiative forcing in a temporal manner (Fouquet et al., 2015). The studies by Peñaloza et al. (2016) and Garcia et al. (2020) comprehensively tested both scenarios. Their results showed that, similar to other studies, the timing of emissions has a significant impact on the results of an LCA in terms of GWP, with the timing of accounting for CO_2 uptake being more sensitive to the final results than the type of method used in the study. For this reason, they confirmed the preposition that if the focus is on short-term climate mitigation in terms of sustainability, the *regrowth* scenario should be used (Garcia et al., 2020).

1.2.3. Rotation and storage periods

In addition to determining on the specific time period in which the emissions occur, the rotation period was found to be of great importance in the study by Cherubini et al. (2011). Whilst initially focusing on bioenergy, they found that the effect of biogenic carbon emissions on global warming is related to the period of biomass regrowth. Figure 5 is from the same study and shows how the carbon stock before harvesting and release to the atmosphere (point a) is able to grow back and reach its previous amount of carbon (c). In the case of replanting the same type of biomass, the time that is required to sequester the same amount of carbon that was released is called the rotation period (Cherubini et al., 2011).

The study from Guest et al. (2013) decided to apply this information to bio-based materials and evaluated the impact of these rotation periods on global warming by calculating characterization factors (CFs). The amount of time between the start of biomass regrowth and the release back into the atmosphere, called the storage period, is also included in these CFs. Using a complex model called the Bern IF, they studied how CO_2 decays after release and how quickly biomass (trees, plants) *regrows*. The study showed that if biomass is stored longer and regrows quickly, it spends less time in the atmosphere as CO_2 and thus has a lower global warming potential (Guest et al., 2013).

Conversely, if biomass is stored for a short time and takes longer to regrow, it temporarily increases atmospheric CO_2 levels. Based on their findings, they developed a method for calculating the GWP of biogenic emissions as a function of storage period and the rotation period, called the GWP-bio index. Based on their research, they generated CFs by plotting storage periods (ranging from 0 to 100 years) against rotation periods (ranging from 1 to 100 years). To illustrate, for a rotation period of 100 years (CLT grown in Germany) and a storage period of 80 years, the denoted GWP-bio index factor value is -0.27. Here, the minus represents a decrease in GWP, where a longer rotation period means a lower value and thus a smaller decrease in GWP (Guest et al., 2013).

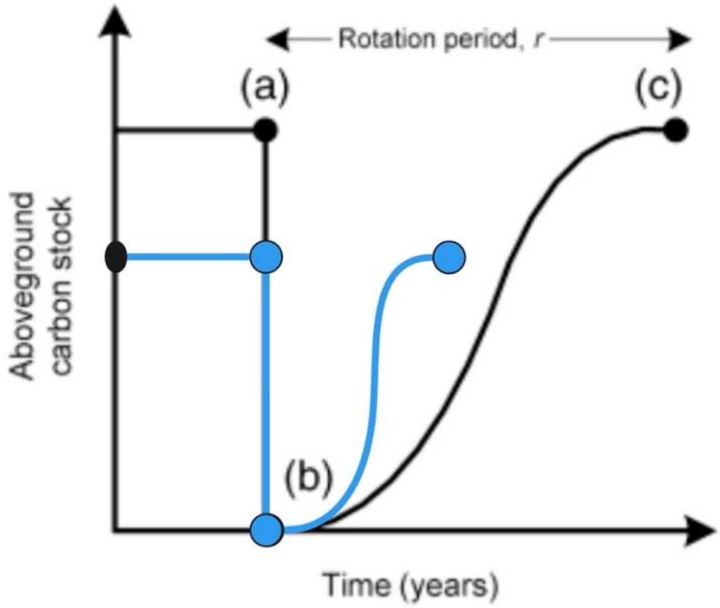


Figure 5: Graphic illustration of the rotation period of mass timber (Cherubini et al., 2011, p. 416), added with a blue line that represents a faster growing bio-based material (i.e., straw or bamboo).

Pittau et al. (2018) conducted a more in-depth study of the impact of these rotation periods on global warming with different bio-based materials. By incorporating the carbon cycle and the timing of emissions, they primarily showed a large difference in the results compared to using a conventional static LCA, again demonstrating the importance of including time in environmental assessments. However, they also highlighted the fact that the rotation periods may be different for other bio-based materials. Straw and hemp are for instance known to be fast-growing materials that can be completely regenerated after one year. They can thus serve as a promising opportunity for rapid carbon sequestration, with their rough difference from forest products represented by the blue line in Figure 5. Due to its slow forest regrowth, Pittau et al. (2018) argued that mass timber could not be considered as a carbon-neutral material in a short time horizon, and therefore not be suitable as a climate change mitigation strategy.

While the effect of time can be considered highly significant in terms of global warming, it is also highly dependent on its storage capacity (Skullestad et al., 2016). If a fast-growing type of biomass, such as straw, is capable of having a long storage period, it could reduce atmospheric CO_2 levels for a period of time. On the other hand, if it is stored for a short period of time, it could temporarily increase atmospheric CO_2 levels. This is also shown in Figure 5, which explains that the GWP effect depends on when the CO_2 is absorbed and released, not necessarily on the type of biomass. As shown by the GWP-bio index, in the case of a long-lived product such as a building, if the CO_2 is absorbed by new trees before the CO_2 is released from the old trees, it temporarily reduces the greenhouse effect and can be used as a way to mitigate climate change (Skullestad et al., 2016).

1.2.4. End-of-life scenarios

The GWP-bio index from Guest et al. (2013) showed that if a long enough storage period is combined with a short rotation period, it will results a temporary decrease of atmospheric CO_2 in that specific time horizon. If the sustainable forest management assumption is fulfilled, the practice of storing carbon in long-lived products can become beneficial (J. H. Andersen et al., 2022). The importance of the storage period is because of this highly dependent on the service life of the building but is also related to end-of-life (EoL) practices of the wood product. Whereas it has been claimed that the consideration of the EoL phase is crucial for the biogenic carbon accounting since a positive amount of emissions is released at this stage (Hoxha et al., 2020), there still remains uncertainty on the allocation methods (Garcia et al., 2020). After its service life in the building, there are typically four possible options for wood products; they can be reused/recycled, end up in landfill or incinerated. The amount of biogenic carbon that will stay in the product or be released depends on the chosen fate, as shown before in Figure 1 (WoodWorks, n.d.).

The majority of the wooden panels that have been used as the structure of a building are considered inadequate for further use and is sent to landfills to decompose (Kwok et al., 2020). A portion of the biogenic carbon that was stored in the product are released during this decomposing process as carbon dioxide and methane emissions (Milota & Puettmann, 2017). These are called landfill gases and contribute greatly towards global warming due to the higher GWP potential of methane. In the carbon neutral approaches, it is believed that these are the emissions which compensate for the stored biogenic carbon in the product and manufacturing stages (Hoxha et al., 2020). However, a significant portion of carbon could also be stored indefinitely in these landfills. The cut-off point for this permanent storage is 100 years and is then considered not to leave the product system, meaning the biogenic carbon is not released back into the atmosphere within the time horizon of an LCA (Kwok et al., 2019). Where there is a bit of uncertainty how much carbon is stored, recent LCA studies use the Athena software for their calculations which sets a permanent carbon storage of 61% within the EoL stage (Allan & Phillips, 2021; Kumar et al., 2024).

Incineration is another EoL-scenario for wood products and is most typically done at a bioenergy power plant (Kwok et al., 2019). Direct incineration will lead to instant release of all biogenic carbon that is inside the biomass of the material, producing both electricity and heat energy. In most cases, this energy recovery from the combusted material is directly released into the atmosphere as CO_2 (Milota & Puettmann, 2017). The case studies of Kwok et al. (2019) on the other hand took the assumption that the generated power could potentially avoid the use of another type of energy generation, for instance by the use of fossil fuels. This benefit of “avoided fossil fuel use” is subsequently placed in another LCA module (D) and was the main reason for their negative GWP results, which was also found in another study stating that the release of the stored carbon can be avoided by reusing or combusting the product as a substitute of fossil fuel (Felmer et al., 2022).

The direct reuse of the full wooden panels is generally considered to be the preferred option over the other EoL scenarios in terms of environmental impact (Kwok et al., 2020). Due to the prefabricated nature of the CLT panels, disassembling or additional processing of the material are often not needed, and transportation emissions are limited. Reusing the wood will extent the storage period of the wood and outweigh its species' rotation period, hereby creating a positive effect on atmospheric CO_2 (Guest et al., 2013). It was found that directly reusing CLT or glulam after its use in the construction can result in at least 75% of the initial biogenic carbon being successfully stored in the wood for long-term (Greene et al., 2023). Even though reusing the panels directly is preferred, recycling is the more probable scenario. Although the recycling the wooden panels into wood chips or panel products induce more emissions related to transport and processing, a benefit of avoiding the harvest of virgin wood from the forest could be argued and also placed in module D (Kwok et al., 2019).

Each EoL allocation has a different impact on the environment with regards to biogenic carbon, where Morris (2016) found that incineration was the least favorable option, especially when it was combined with the substitution of natural gas. Regardless of the impact, 'realistic' EoL scenarios have been generated by various LCA software like the Athena Impact Estimator (Allan & Phillips, 2021; Kumar et al., 2024) and Tally (Kwok et al., 2019) through setting a certain percentage on the share that is landfilled, reused/ recycled and incinerated. These are however not identical across the software and hereby lead to differences in results. Garcia et al.'s (2020) study also focused on various EoL methods and its impact on biogenic carbon emissions. They concluded that it is highly affected by the chosen method of biogenic carbon accounting, where the practitioner should either allocate these emissions at the end of its lifetime in a manner that aligns with the chosen accounting method. Alternatively, the benefits of temporary biogenic carbon storage during its use phase rather than at the point of emission during EoL combustion. This approach eliminates the need for specific EoL allocation for biogenic carbon, allowing standard EoL decisions to be applicable for the study (Garcia et al., 2020)

This section again showed the difficulty and variety in making assumptions in LCA methodologies, in this case for EoL decisions. Besides the issues within EoL fates, the rest of the findings collectively demonstrated that other influential factors like rotation and storage periods and the setting of temporal boundaries are similarly causing problems. Even though it is acknowledged that these factors cannot be neglected in these environmental assessments, there does not seem to be a consensus on how to treat these factors. The need for harmonization on these discussion points among researchers is high in order for LCAs to fit their purpose in terms of reliability. A solid framework and internationally recognized standards or guidelines for accounting biogenic carbon would likely facilitate these kinds of developments.

1.3. Current LCA guidelines

1.3.1. European standards

The trustworthiness and reliability of LCA depends on its adherence to formulated global standards. The International Organization for Standardization (ISO) provides standardization on a global level and creates the general standards for the industry, such as the 14040 and 14044. These two focus on guidelines for conducting LCA in a broad sense. The one most relevant to this research is “ISO 21930:2017 Sustainability in Buildings and Civil Engineering Works - Core Rules for Environmental Product Declarations of Construction Products and Services” (ISO, 2017). Within the European Union (EU), EN 15978 (CEN, 2011) and 15804+A2 (CEN, 2019) are the most relevant guidelines to follow when performing an environmental impact assessment for a given product or building. Within these documents, rules are presented on how to perform the environmental analyses, also in relation to biogenic carbon. The European documents are more specific and applicable to the current study, so this chapter will focus on EN 15978 and EN 15804, including a brief notation of the EN 16449 which concerns the calculation method of CO_2 sequestration in wood-based products (CEN, 2014).

EN 15978 (CEN, 2011) is mainly used for calculation rules for new and existing buildings, where it provides the inventory analysis procedure, a list of indicators and the related procedures, data requirements and the system boundaries. The system boundaries are illustrated in Figure 6 using the different modules of the building life cycle. Modules A1 to A3 cover the product stage in terms of raw material procurement and manufacturing processes (CEN, 2011). Modules A4 and A5 represent the transport and construction/installation respectively, while Module B is referred to as the use stage and includes the maintenance and operating of the building. Module C is the EoL phase and focuses on what happens with the materials when the building is demolished. Finally, Module D contains information beyond the system boundaries, adding potential benefits to the chosen EoL fate (CEN, 2011). Each system boundary also has a name depending on which modules have been included by the practitioner (i.e., cradle-to-grave).

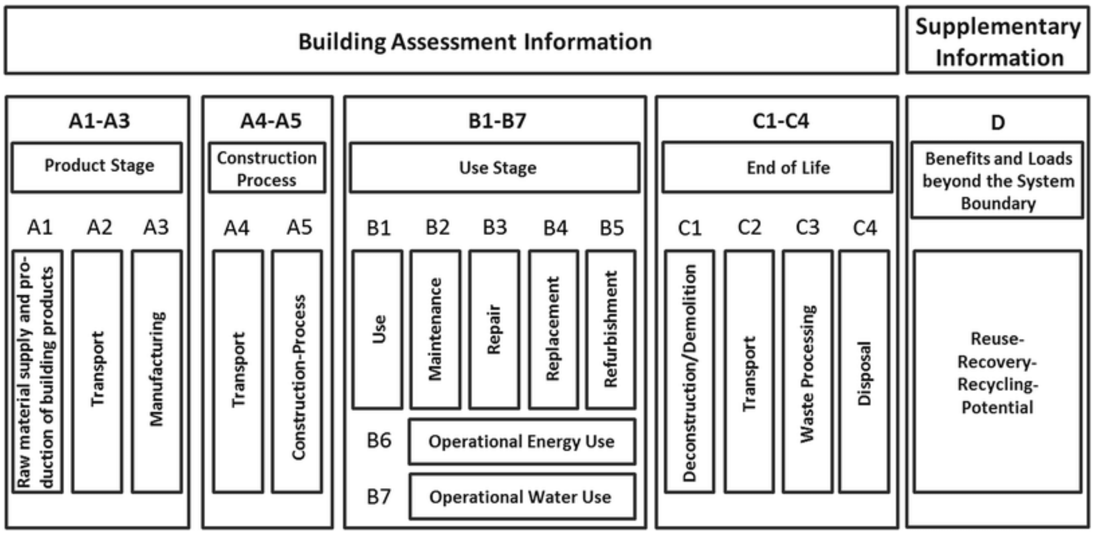


Figure 6: System boundaries with its corresponding modules according to EN 15978 (CEN, 2011).

The consideration of biogenic carbon is not present in EN 15978 due to its broader focus on the system level. The EN 15804 standard, on the other hand, focuses more on the product level, in particular the product category rules (PCRs) for all construction services (CEN, 2019). The standards consist mainly of Environmental Product Declarations (EPDs) for LCA at product level. These EPDs are used for clear communication, transparency and objectivity and contain environmental information about a specific material or product. They provide a general overview of products and thus very useful summarized information for the preparation of an LCA (CEN, 2019). The major purpose of the PCRs is that these EPDs are verified and harmonized for accurate comparability, so that the trustworthiness of the LCA result does not depend on the choices made by the practitioner (Andersen et al., 2022).

In 2019, the EN15804 was revised (version A2) and included several important additions to the primary version (CEN, 2019). Most relevant to this study, EN15804 + A2 added eight new environmental impact indicators, increasing the number of indicators from 11 to 19 (CEN, 2019). Within all EPDs, the most common indicator is the Global Warming Potential (GWP), which provides information of on greenhouse gas (GHG) emissions and the corresponding contribution to global warming (IPCC, 2023). Previously a single indicator, it is now divided into four variants: total, fossil, biogenic, and luluc. GWP-fossil and GWP-biogenic include only emissions from fossil and biogenic sources, respectively. GWP-luluc represents land use and land use change, and naturally includes only the emissions caused by this specific phenomenon. Finally, GWP-total represents the sum of all the emissions caused by the GHG (CEN, 2019).

The reporting of biogenic carbon has only been introduced in the updated version that the (CEN, 2019). In addition to the added variants of impact indicators, the reporting of biogenic carbon mass is now required in the EPDs. While this is preferable to the previous version, it is still not mandatory to include it in the methodological part of the LCA. An important and relevant change in EN15804 + A2 is the mandatory selection of possible system boundaries with respect to the life cycle phases in EPDs. For biogenic carbon, this means that depending on the scope of the LCA (i.e. cradle-to-grave), the practitioner is not allowed to exclude or include any of the modules according to that specific scope. As a result, accounting for biogenic carbon is not allowed in a cradle-to-gate scope because the standard maintains the carbon neutrality approach. The reasoning behind this is that if only Module A is considered in an LCA (i.e. cradle-to-gate), the biogenic carbon would create a negative value and is therefore unrealistic, following a similar reasoning as Hoxha et al. (2020). In cases that follow a cradle-to-grave boundary, the PCRs of EN15804 + A2 recommend following the -1/+1 approach, which is also followed by the international ISO 21930 (CEN, 2019; ISO, 2017).

In terms of EoL allocation, the updated version now allows the modeler now to calculate and account for the benefits and loads of Module D in the life cycle (CEN, 2019). In terms of biogenic carbon, this means that in the direct reuse, recycling and incineration with energy recovery scenario, the wood product leaves the product system with the stored biogenic carbon as a positive value in module C and is used as an input for the new system in the second building, resulting in a net zero biogenic carbon flow. Therefore, the credit for avoiding the production of a new wood product is only present in the new product system or in Module D (CEN, 2019). According to the biogenic carbon flow diagram of ISO 21930 shown in Figure X, only the landfilling scenario can result in a negative biogenic carbon balance for this specific product system due to the fraction of indefinite storage (ISO, 2017).

Other benefits in EoL decisions related to biogenic carbon (i.e., avoided fossil fuel use and harvesting of virgin wood products) are assigned to Module D because they occur outside the system boundary (CEN, 2019). This can potentially change the GWP results if the practitioner chooses to do so, although numerous studies debate whether the EoL scenarios are able to avoid the release of biogenic carbon at the EoL. To actually claim these benefits in the area of bio-based materials is an ongoing discussion in the literature and is beyond the scope of this research. Making the right end-of-life decision is undoubtedly important for the life cycle of a product. However, this study will focus on the temporary storage of biogenic carbon within the life cycle of the wood product (Modules A-C), excluding the potential benefits outside the system boundary (Module D).

Lastly, the calculation of initial CO_2 sequestration in wooden products is done according to the calculation method derived from the standard EN 16449 “Wood and wood-based products - Calculation of sequestration of atmospheric carbon dioxide” (CEN, 2014). This document was prepared by the European standardization committee TC 175 WI and describes the practices on how to quantify the amount of atmospheric carbon dioxide based on the biogenic carbon content of wood. Based on other characteristics such as volume and moisture content of the product, the following formula should be used:

$$P_{CO2} = \frac{44}{12} \times cf \times \frac{\rho_{\omega} \times V_{\omega}}{1 + \frac{\omega}{100}}$$

Where cf is the carbon fraction oven dry mass of the wood product (0,5 as the default value); ω is the moisture content of the product, ρ_ω is the density at this moisture content (in kg/m^3); V_ω is the volume at this moisture content (in m^3). The P_{CO2} is final result of the formula and represents the oxidized biogenic carbon as atmospheric carbon dioxide emission from the product system. This wood calculation module, in the form of a European guideline, has thus provided a harmonization for an accurate and realistic representation of the amount of CO_2 sequestered in wood (CEN, 2014).

1.3.2. Dutch standards

The standards for the environmental performance of Dutch buildings are based on the calculation of the MPG, or Milieuprestatie Gebouwen in full (Quist, 2024). The MPG, similar to the LCA, indicates the environmental impact of all building products but it is typically calculated by the summing the impact categories from the LCA results and then linking them to a monetary value. Together, they form a final score that is expressed in euros per square meter per year, often referred to as the shadow cost. To illustrate, an MPG score of 1 essentially means that a given building cannot exceed an annual average of 1 euro of environmental damage per square meter, given the impact results of the LCA. It is considered a critical measure for determining the sustainability of buildings in the Netherlands, where it is mandatory to be able to obtain an environmental permit for the construction of new buildings and existing offices larger than 100 square meters (Quist, 2024).

Due to the increasing awareness of sustainability in the building sector, the Dutch Minister of Housing has requested that the MPG be set at 0.5 (previously 0.8) for new dwellings as of January 1, 2025 (Jonge, 2023). In addition to the stricter guidelines, the methodology for calculating the MPG will undergo several changes to bring it in line with the updated European standards. The goal of these changes was meant to achieve more sustainable construction, specifically by promoting circular and bio-based construction. However, by following the updated European standards (EN15804 + A2) and including the eight new impact categories, the results for mass timber buildings are actually less favorable, thus discouraging bio-based building (Jonge, 2024). This has logically led to some criticism of the proposal and people working in the sector have pleaded for several improvements (Houtblad, 2024).

In a *position paper* by the Dutch Green Building Council and Gideon (Nossek et al., 2023), the authors discuss three main points of improvement in the methodology; 1) the inclusion of module B6 in the calculations, 2) the exclusion of module D in the calculations, and 3) how to consider and account for biogenic carbon storage. On the latter point, they argue for the documentation of the biogenic carbon in the national accounts and for a net emissions figure at the end of the MPG calculation. This would not only benefit the transparency and communication of biogenic carbon in general, but would also result in a more favorable MPG score and thus stimulate the use of bio-based materials in the construction industry (Nossek et al., 2023).

As a result of these mixed reactions, the Minister decided to postpone the adjustment of the MPG until July 1, 2025, in order to review the complications that have arisen and to improve the proposal together with the sector. In the same letter to the House of Representatives, the Minister stated that the new form of the MPG requirements does not currently take into account the potential benefits of carbon storage (Jonge, 2023). He mentioned that the European Commission is currently working on a "whole-life-carbon" policy, which will be part of the new European standards for building and construction enforced by the Energy Performance of Buildings Directive (EPBD). The minister is not eager to deviate from this and wants to align the results of the policy with the MPG, much to the dissatisfaction of the construction industry (Houtblad, 2024).

1.4. Problem definitions

1.4.1. Previous results and knowledge gaps

Besides the numerous dynamic proposals by experts in the field (Cherubini et al., 2011; Guest et al., 2013; Levasseur et al., 2010), there are enough other studies that highlight the problems with static biogenic carbon accounting in LCA. Salazar & Bergman (2013) have created a time-zero equivalent by including cumulative radiative forcing (RF), which results in emissions that occur closer to the end of the time span having a smaller effect on global warming than it in the traditional impact indicator. Their results therefore show a larger spread as the service life of the building is extended (Salazar & Bergman, 2013). Similarly, another approached by Vogtlander et al. (2014) is based on the global carbon cycle and land use change. They argue that there can only be a benefit of carbon sequestration in terms of biogenic carbon if there is a global forest growth and simultaneous growth in the use of wood in the building sector (Vogtlander et al., 2014).

A Norwegian study agrees with the above proposition of RF, stating that engineered wood can cause a temporary reduction of RF in the atmosphere if the production leads to the sequestration of biogenic CO_2 before its release and the rotation period of the wood species rotation period is short enough (Skullestad et al., 2016). This type of removal of CO_2 from the atmosphere will also affect how much CO_2 is absorbed by oceans and land. Simply adding up CO_2 emissions over a short time horizon (as is done in LCA) does not provide the full picture because the atmosphere, oceans, and land are all interconnected (Skullestad et al., 2016). Although it is extremely difficult to account for all fluxes in a single LCA study, time horizons other than the 100 years advocated by the IPCC (Pörtner et al., 2022) also seem to influence the results of such environmental assessments.

Where the European and Dutch standards ignore the relevant findings from these researchers, one of the most recent papers focusing on temporal considerations found that the environmental impact of wood products is highly dependent on the method used (C. E. Andersen et al., 2024). By studying eight different scenarios varying between service life of buildings, time horizons, and time periods, they highlighted the fact that the biogenic carbon accounting principles are the main cause of the inconsistency of impact results (static vs dynamic methods). The discounting of future emissions and its relation to the time horizon was found to be less influential (C. E. Andersen et al., 2024).

J. H. Andersen et al. (2022) see the main problem in the lack of consensus between the approaches currently used. The whole discussion is embedded in the lack of comparability between the different studies on bio-based materials as a consequence of the lack of consensus. LCA is intented to be a reliable and trustworthy source for assessing environmental performance, which is currently undermined in relation to mass timber buildings by the approach and standards chosen by practitioners. While the 0/0 approach is supposed to be recommended in the current literature as it neutralizes the problems associated with biogenic carbon, it does not take into account the potential benefits in terms of temporary carbon storage. A harmonization process involving the key researchers in the field in cooperation with the standardization organizations (ISO and CEN) could be a start to find the ideal solution to the problem (J. H. Andersen et al., 2022).

1.4.2. Hypotheses and research questions

The temporal and correct inclusion of biogenic carbon is important to reflect the true environmental performance of a bio-based material. The carbon neutrality enforced by the European and Dutch standards does not reflect the reality of biogenic carbon emissions of bio-based materials, where influencing factors that affect the timing, such as replanting a forest system and rotation periods are not considered in the current standards and the system boundaries of LCA. A recent Master's thesis by van den Berg (2023) has already addressed the discrepancies between European standards and the current practices for accounting for biogenic carbon in LCA. Through an extensive review of the available literature, the author demonstrated that there is no clear consensus and harmonization among practitioners, while a change in the methodology is needed. However, the research was unable to reach a conclusion on the single best approach for accounting for biogenic carbon (van den Berg, 2023). It was therefore recommended that further research be conducted and that a practical case study of a recent mass timber construction project be included to provide a better perspective on the different methodologies. Combined with the other findings in the available literature, this report will conduct research that will serve the following three purposes:

1. To discover the impact of the key influential factors across the various biogenic carbon accounting practices from the LCA methodological perspective (i.e., rotation period, involvement of replantation system, EoL decisions etc.)
2. To find out how the different carbon accounting methods influence the choices of construction materials from the construction sector's perspective
3. To initiate a harmonization process among research that could potentially lead to a consensus for the most reliable method of biogenic carbon accounting

As previous studies have repeatedly shown, the impact of the influencing factors will vary depending on their characteristics. The length of the rotation and storage periods, the decisions on the end-of-life and the replanting system are most likely be able to change the results of the LCA. With a dynamic model, a fair allocation of these factors could then influence the decision-making processes in the construction sector, as the results will more accurately reflect the reality of the environmental performance of a building. If the European and Dutch regulations and guidelines considered, a harmonization process of the biogenic carbon accounting methodology could be initiated.

This research could help to bring clarity and support the harmonization processes by testing these different hypotheses in a case study. Before setting up this case study, the findings of the literature review and the associated hypotheses will primarily be compared with a systematic review of all relevant published LCA studies. In this way, the results of the two reviews (literature and systematic) can be linked in a targeted manner to guide the design of the practical case study. The case study will consequently test the different methodological choices and thus extend the existing research that has already been done on this topic. In order to contribute to the harmonization process and to create a consensus for biogenic carbon accounting, the following research question is formulated and will be answered at the end of this study:

What is the impact of the different biogenic carbon accounting methods in the LCA of mass timber buildings?

Since the problems identified in the literature are numerous and require several steps to address, it is useful to break down the main research question down into sub-questions that will allow for the research design and its methodology to be set up accordingly.

1. *How is biogenic carbon modeled in recent LCA studies and how does the inclusion of temporal factors affect the results?*
2. *How can the literature findings contribute to the harmonization process of accounting for biogenic carbon in LCA?*
3. *To what extent do the different biogenic carbon accounting approaches lead to alternative GWP results for the CLT case study building “SAWA” in Rotterdam?*

This research is conducted for the purpose of a master thesis from a student of the joint degree program Industrial Ecology from Leiden University and TU Delft. The research objective has been developed through several discussions with Mark Compreer from Nice Developers, Dr. Hu of Leiden University and Dr. Meijer of TU Delft, the latter two being the official supervisors of this study. Robert Platje of Mei Architects also helped with data and filling in the gaps. These people from different institutions have inspired the main research question of investigating the impact of different biogenic carbon accounting methods and have therefore jointly contributed to the final deliverable of the master thesis.

The remainder of this paper will be divided into several parts. The next chapter (2) focuses on the systematic review, including its framework and methodological design. At the end of this chapter, a list of the main findings of the systematic review will be presented. Chapter 3 builds on these findings and presents a potential framework in the form of a decision tree, which will be tested in the following chapter. Chapter 4 presents the guidelines of the simplified LCA case study (i.e., goal and scope definition, inventory analysis) and will clearly present the results obtained. Chapter 5 then compares, interprets and discusses the main findings of both analyses, including their limitations and suggestions for further research, while the last chapter (6) concludes the whole report.

2. Systematic Review

2.1. Methodological framework

Based on the research objective and related questions, this study consists of two main methodological parts. The first part was carried out in the form of a systematic review, with the aim of extending the work of van den Berg (2023) and the other previous research. It comprehensively reviewed and classified all relevant LCA case studies conducted on mass timber construction, and specifically examined how different choices of biogenic carbon accounting methods have led to different assessment results. This part thus corresponds to the first sub question:

- *How is biogenic carbon modeled in recent LCA studies and how does the inclusion of temporal factors affect the results?*

A systematic review is more than just a collection of studies, where it critically analyzes the identified data from the relevant research that exists (Siddaway et al., 2019). Systematic reviews become more useful when a particular theory is developed and, consequently, has practical implications for decision-making processes. In most cases, this is the purpose of such a review. In this study, the literature on the topic was not simply summarized, but critically integrated and a coherent synthesis of the methodological differences in the results of existing LCA studies was provided. The results were structured with a focus on biogenic carbon in order to build a theory (i.e., decision tree) that could then be tested with the practical LCA case study based on the different accounting methodologies.

Due to time constraints, studies were selected that would achieve the intended results of the review. This process depends on several factors and is visualized in Figure 7. The (sub) research questions belong to the first step of scoping, where the keywords in these questions can be used to search the databases (Scopus and Web of Science). These keywords are “mass timber”, “cross laminated timber”, “Life Cycle Assessment”, and “bio-based” including some synonyms and variations. The next factor that determines the scope of the systematic review is the already conducted reviews on mass timber LCAs, for example by Duan et al. (2022) and Younis & Dodoo (2022). Where they addressed differences in LCA results of different types of mass timber and provided a clear and comprehensive overview of these studies, they did not focus on differences in biogenic carbon accounting. The study by Hoxha et al. (2020) was more focused on this aspect of biogenic carbon and will probably be the most similar to this review, but they made the decision to include only European and international standards and EPDs. This has created the need for a systematic review of LCA studies by critically analyzing the specific biogenic carbon accounting methodologies of the investigated peer-reviewed papers.

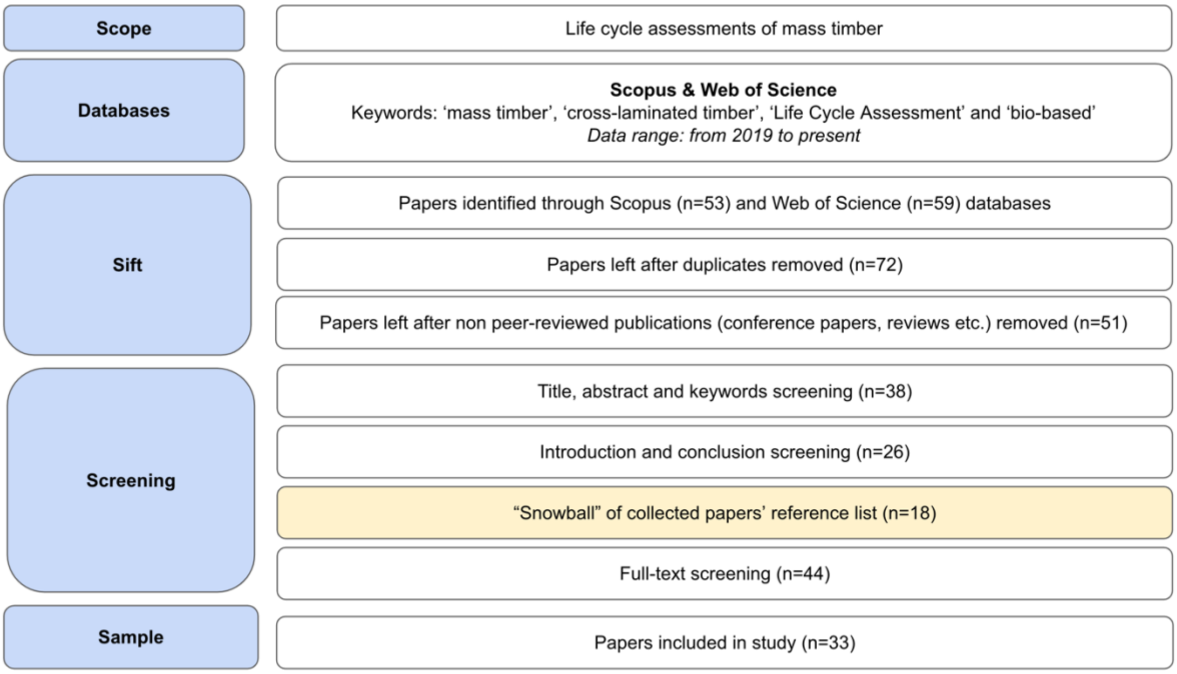


Figure 7: Stepwise overview of systematic literature search, based on the paper from Siddaway et al. (2019).

The next important step in conducting a systematic review is the notation of inclusion and exclusion criteria for specific studies to further define the boundaries of the review (Siddaway et al., 2019). The first and most fundamental exclusion criterion is the temporal scope of the review, which was set to 2019 and beyond. This is because this study is primarily interested in the most recent developments in methodological choices and their relation to the updated standards. 2019 was the moment when the reporting of biogenic carbon was introduced in the updated version of the EN15804+A2 (2019), thus changing the overall concept of this aspect in in LCA. Some exclusion steps were more obvious, such as the removal of duplicates, conference papers, book chapters and other reviews where the search was also limited to English-only papers. Title, abstract and keyword screening, followed by full-text screening, led to further filtering, which was based on the following set of criteria:

- The study must be complete
- The study must be about the building sector
- The LCA or studying environmental impact must be the main analysis in the study
- The study must be about either entire buildings, building parts or other constructions (i.e., garages)
- The study must be about a form of mass timber (i.e., CLT, Glulam etc.)
- The study must be about the life cycle of a new construction, no renovations or extensions
- Studies that only focused on a specific aspect of its life cycle (i.e., transportation or wood species) were excluded

Within the reference lists of the collected literature from the databases additional relevant articles were found through the so-called 'snowball' search (Siddaway et al., 2019). This resulted in an additional 18 articles, ensuring that no important articles were omitted from the study. During the full-text screening process, a certain number of borderline cases were decided to be excluded from the review. There were several reasons for this, but the most important one was that the LCA just focused on a specific element of the life cycle (e.g. transportation). Two specific studies did not use any of the official LCA standards and did not specify the system boundaries or life cycle stages included (Dodoo, 2019; Lechón et al., 2021), making them too unreliable for inclusion. Other examples of borderline cases were ambiguity of results (Zeitz et al., 2019), use of simulations of buildings instead of real ones, and more focus on other types of analyses instead of the LCA (e.g., LCC or energy analysis). Excluding of these borderline cases resulted in a final number of 33 studies that were used for the systematic review.

The journal articles selected for inclusion were then studied comprehensively with a special focus on biogenic carbon. In addition to the general statistics of the papers, such as location, floor area and material use, there are several elements that are important for the accounting of biogenic carbon in an LCA, which were discussed in detail in previous chapter. The first relevant characteristic is the context in which the LCA was conducted. This is important for assess whether the authors used the most recent international or European standards and how this might lead to different results. Since the GWP impact indicator is the only applicable category for biogenic carbon, this was the only value that was noted. In addition, it was reviewed whether or not this particular GWP-score included accounting for biogenic carbon. The specific approach to biogenic carbon was further evaluated, where one of the known approaches (0/0, -1/+1, Dynamic) found. These approaches were examined more in detail, looking specifically at how they accounted for the biogenic carbon in their LCA, including a possible rationale or explanation for doing so. If a study calculated both its GWP-values with and without biogenic carbon, this was also documented.

2.2. Results

2.2.1. General statistics

Of the documents examined in the systematic review *(n=33)*, all but one were peer-reviewed papers. The study by Hellmeister (2022) is a master's Thesis from the University of Maine, but although it is not a journal article, it was considered in another peer-reviewed study (Kumar et al., 2024) and furthermore qualifies as a relevant article for this study. Five of the collected papers are from Kwok et al. (2019) and are from the same document. The reason why this was not considered as a single publication is because their work is a collective report in which they studied five different buildings or constructions separately and analyzed them together. These five constructions are very different from each other, in terms of building profiles, location and system boundaries and they also extensively discussed their biogenic carbon accounting method.

In terms of demographics, all continents except Africa are represented in this review. The most striking aspect is that the most common location of the studies is the United States (14), followed by Norway (3), Sweden (3), Spain (2), and China (1). The city of Portland is represented four times, two of them by roughly the same authors studying exactly the same building (Liang et al., 2020, 2021). However, one focuses on the entire life cycle of the building (cradle-to-grave), while the other focuses only on the production and manufacturing part (cradle-to-gate). There is a great variety in the system boundaries of the life cycles, with each study naturally choosing to include or exclude certain modules depending on the purpose of their LCA. The majority of studies chose to conduct their LCA in a cradle-to-grave study (23), others in a cradle-to-gate study (8) and one out of the 32 studies used a cradle-to-usage approach. This diversity in the documents reviewed also applies to building height, floor area and year of publication. All the necessary information can be found in Appendix A.

2.2.2. Biogenic carbon accounting

Of the 33 papers reviewed, the majority (26) included some form of biogenic carbon in their analysis. Seven of these chose not to include a calculation or other form of allocation in the analyses, two of which simply did not mention any form of the word “biogenic carbon” (Balasbaneh & Sher, 2021; Jayalath et al., 2020). 30 studies followed the carbon neutrality assumption, with 12 of them choosing not to represent biogenic fluxes with the 0/0 approach. The other 18 followed the norm of to the European standards with -1/+1 approach, while the remaining three studies used dynamic modelling and deviated from the carbon neutrality principle. Regarding the different standards, the European EN 15978 (24) was the most used among the studied documents, followed by a combination of the international ISO 14040 and 14044 (14). The EN 15804 was used eight times. All statistics related to biogenic carbon can be found in Appendix A.

Three out of the total number of papers included a temporal aspect in their biogenic carbon calculation. J. H. Andersen et al. (2022) calculated a base scenario and a biogenic carbon scenario for their mass timber building. In this scenario, the GWP-bio index was estimated based on the method of Guest et al. (2013) to test the effect of temporary carbon storage, which resulted in a 36% reduction in terms of GWP compared to their base scenario (J. H. Andersen et al., 2022). Another paper that did not follow the carbon neutrality rule is the master’s thesis by Hellmeister (2022). In this study, the GWP score was calculated based on the assumption that forest growth removes carbon dioxide from the atmosphere. Based on the estimate of carbon storage associated with forest regrowth, the positive emissions from CLT production were subtracted from this figure and assigned to the product itself (Modules A1-A3), resulting in a GWP of -487 kg CO_2-eq/m^2 (Hellmeister, 2022).

Hoxha and colleagues (2020) compared the three existing methodologies, including both scenarios of the dynamic approach of Levasseur et al. (2010). Their results showed that in the dynamic approach, a large part of the biogenic carbon in the product and construction phase is emitted from wood residues during the processing of mass timber products in sawmills. In addition, as shown in Figure 8, since the service life of the building (storage period) was only half the rotation period of the forest, the carbon uptake from forest *regrowth* (right) accounted for only 8%. Considering the *growth* scenario (left), the amount was significantly higher due its completed rotation period before harvesting. However, to promote sustainable forest management and regrowth, the *regrowth* scenario should be preferred (Hoxha et al., 2020).

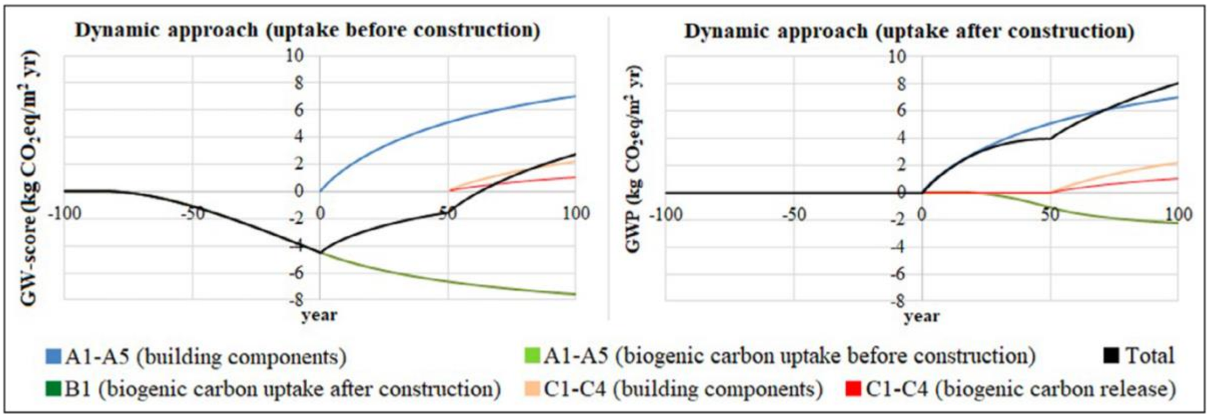


Figure 8: Difference in results between *growth* and *regrowth* scenarios from Hoxha et al. (2020)

Another group of studies found potential benefits for wood products beyond the system boundaries. Both Kumar et al. (2024) and Allan & Phillips (2021) used the Athena IE4B software, which calculates the sequestered biogenic carbon and reports it in the last module of the life cycle (D). This software assumes that some part of the biomass in the wood product does not decay or burn, thereby permanently storing carbon. This percentage of 61.6% thus serves as a negative number in their model and resulted in a reduction of the GWP score that varied from 69-89% (Kumar et al., 2024). These negative emissions are commonly referred to as “avoided fossil fuel use”, and this approach was also found in the report consisting of five separate case studies by Kwok et al. (2019), where the reduction in GWP ranged from 29-61% depending on the type of construction. In total, this benefit for wood products in Module D was present in ten of the studies reviewed, where the importance of reusing mass timber after its lifetime was also demonstrated in the form of a negative GWP score (Greene et al., 2023).

Similarly, cradle-to-gate (with options) LCAs that include biogenic carbon can produce more favorable GWP results while maintaining the carbon neutrality assumption, as found in six studies. Felmer et al. (2022) demonstrated this by achieving a GWP score of -186 including biogenic carbon. This type of analysis includes only the carbon uptake in Module A, without examining the module where the release occurs (C or D). While it is ambiguous to assume this as a potential benefit, their study also argued that the release of the stored carbon can be avoided by reusing or combusting the product as a substitute for fossil fuels in various end-of-life scenarios (Felmer et al., 2022).

A few of the remaining papers made the decision not to include biogenic carbon flows in their study based on the neutrality principle, where they combined this with a 0/0 approach. However, some studies considered biogenic carbon separately without including it in their GWP score. An example of this is the study by Hart et al. (2021), who mentioned that temporary carbon storage was not assessed in their core LCA, but added its benefits in their sensitivity analysis. This work was then also classified under 'inclusion of biogenic carbon', which explains why several studies are similarly combined with a 0/0 approach in Table X. Similarly, although Nakano et al. (2020) maintained the carbon neutrality principle, their cradle-to-gate study showed a potential reduction in the overall GWP score when biogenic carbon was taken into account, depending on end-of-life decisions.

To sum up, a total of 12 studies out of the 33 did not include biogenic carbon flows in their LCA, following the 0/0 approach. 18 papers adhered to the LCA guidelines and applied a CF of -1 for the uptake and 1 for the release within the impact categories. The three studies that modelled the benefits of temporary carbon storage by including temporal aspects each of them chose a different approach. Where Hoxha et al. (2020) method was based on the dynamic CFs developed by Levasseur et al. (2010), J. H. Andersen et al. (2022) applied the GWP-bio index based on rotation and storage periods from Guest et al. (2013). The master thesis from Hellmeister (2022) did not include a very detailed part of the study's methodological choices, but it did mention that "the emissions of wood products are subtracted from the estimated carbon storage associated with forest growth, applied to the product itself (A1-A3), and not the waste (C and D)". Finally, some cradle-to-gate LCAs have produced rather ambiguous results, in which they set the CF for biogenic carbon uptake at -1 while not considering a release at the EoL, whereas others found a vast reduction in their final GWP scores due to module D benefits.

3. Decision tree

3.1. Justification and model set up

The results from the literature and the systematic review have shown that there are several different ways to model biogenic carbon in LCA studies. The predominant method is to treat it as carbon neutral, assuming that it has no significant impact on the climate due to its short carbon cycle (J. H. Andersen et al., 2022). This has also been adopted in the recently updated European standards on EPDs for assessing the sustainability of buildings (CEN, 2019). Previous research has shown that this is not always the case; it depends on how biogenic carbon is used in the product system being assessed and on the management of materials containing biogenic carbon, such as forest plantations, by the supplier (Guest et al., 2013; Levasseur et al., 2010). This discrepancy between the literature and international and European standards for LCA has led to debate and uncertainty, with practitioners ultimately having to decide for themselves which approach to take.

The systematic review of existing LCA studies of mass timber buildings has confirmed the lack of consensus on biogenic carbon accounting in the previous chapter, where it was found that there is a high variability in the approaches used among the papers reviewed. A situation in which LCA studies are not conducted in a similar manner and therefore produce large differences in the final results is not desirable. Not only does this create a lack of comparability and lead to misinterpretations of the environmental impacts of mass timber buildings, but it also reduces the trustworthiness of the assessment itself. In order to maintain confidence in the use of LCA as the main assessment for calculating the environmental impact of buildings, the paper by J. H. Andersen et al. (2022) affirms that a harmonization process is needed to find a single correct way of dealing with biogenic carbon. The subquestion that belongs to this chapter is therefore:

- *How can the literature findings contribute to the harmonization process of accounting for biogenic carbon in LCA?*

A harmonization process can take many forms, with the main purpose being to get all parties involved on the same page as to how the analysis should be conducted. An early example of similar harmonization processes that have been undertaken is the work of Hauschild et al. (2008). A group of developers invented and proposed a new consensus model for modeling chemical effects on humans and ecosystems in LCA, which has been endorsed by the European Commission to date. There is a high probability that there are already ongoing projects like this for biogenic carbon accounting, so this thesis can only play a small role in the whole process. Together with the purpose of the indented case study that will be presented later, a framework in the form of a decision tree was chosen to be able to benefit the most from the current literature in relation to this research.

A decision tree is similar to a flowchart in structure, but instead helps to make decisions or predictions about a particular model (Maksyutov et al., 2019). It consists of nodes that represent decisions on attributes, branches that represent the results of these tests, and leaf nodes that represent the final results or predictions. This type of framework is mostly used for visual representations of a rather complex human decision-making process. It is typically intended to facilitate the understanding and interpretation of these processes, while also providing a way to classify the various outcomes of particular decisions. Decision trees have also been used in the field of LCA, where they previously served as a model for refining the IPCC 2006 guidelines for national greenhouse gas inventories (Maksyutov et al., 2019). This report also emphasized the simplicity of the model, with the idea that complex models often do not lead to improvements in current practice. Especially since the harmonization issue in this study is embedded in the different choices made by LCA practitioners on how to treat biogenic carbon, it could serve as a facilitating tool to find the single best path for all the accompanying issues.

3.2. Criteria

Biogenic carbon has been accounted for in several different ways based on different decision points. By grouping the main findings of the literature into three clusters, the following criteria represent the key decision points for conducting an LCA of bio-based materials:

1. Presence of biogenic carbon in biomass

For products that contain biogenic carbon as a result of the uptake of CO_2 from the atmosphere during biomass growth, the (updated) international, European and Dutch standards together suggest that the associated flows should be noted and be considered in any *cradle-to-grave* LCA that includes bio-based materials (CEN, 2019). As seen in several *cradle-to-gate* studies in the systematic review, including only the uptake of biogenic carbon can lead to biased results due to the negative emissions in Module A. Therefore, it is suggested to always perform full life cycle studies without excluding the EoL stage and limiting the assessment to the product stage only (Hoxha et al., 2020). If for some reason the practitioner decides to exclude the EoL stage, it is recommended not to include biogenic carbon flows at all and to follow the 0/0 approach. This neutralizes the effect of considering biogenic carbon uptake, since the assessment only focuses on fossil-based flows.

2. Temporal factors and forest dynamics

The European standards do not take into account the potential temporary biogenic carbon storage related to forest dynamics. Similarly, very few studies in the systematic review considered this aspect of timing. This means that the carbon neutrality principle (0/0 and -1/+1 approaches) is followed by the majority of recent LCA studies, as proposed by the LCA standards. As argued by Levasseur et al. (2010), the carbon neutrality principle is essentially invalid and can also lead to misleading results. This simplification of a climate neutral forest only holds for short rotation periods, while longer rotation periods require sufficiently long storage periods. For the purposes of climate change mitigation, it is preferable to consider the future timing effect of biogenic carbon emissions (*regrowth* assumption). Both the GWP-bio characterization factors (CFs) and the dynamic model use this method. The two approaches are found to produce similar results, with the application of the GWP-bio index from Guest et al. (2013) being considered the preferred method under the current circumstances (Garcia et al., 2020). A more detailed argumentation for this follows at the end of this chapter.

3. End-of-life allocation (module C)

Hoxha et al. (2020) recommend a mandatory end-of-life (EoL) consideration when considering biogenic carbon due to issues related to uptake and release. When using the static approaches, this implies a ‘normal’ EoL allocation to neutralize the potential problems in these methods. The decision tree therefore follows the proposal of Garcia et al. (2020); either allocate biogenic carbon emissions (at EoL) in accordance with the accounting method used, or, for dynamic models, account for the temporary storage benefits of biogenic carbon storage during its storage (during the use phase rather than at the point of emission at EoL during combustion). This avoids the need for EoL allocation in terms of biogenic carbon, and regular EoL decisions are valid for its study. This is not only the correct way to account for emissions, but also makes EoL decisions less complex.

A small proportion of the LCA studies in the systematic review found that Module D benefits (such as reuse or energy recovery) can influence the final GWP results (Allan & Phillips, 2021; Dodoo et al., 2022; Greene et al., 2023; Kumar et al., 2024; Kwok et al., 2019; Petrović et al., 2023). Through the LCA software or other method, a significant portion of the final GWP result can be reduced by including biogenic carbon benefits in cases of reuse, recycling or energy recovery through incineration. Although there may be a reduction in emissions, previous literature yet also highlights the difficulty of disaggregating them (Garcia et al., 2020). Furthermore, it is not yet clear who can claim the benefit of this emission reduction in terms of biogenic carbon. Due to these uncertainties, this module is excluded from the scope of this study and is recommended to be studied more specifically in future research.

Based on these three criteria listed above, the decision tree facilitation model for biogenic carbon accounting in LCA is shown in Figure 9, where each decision point is linked to a certain (sub)criterion (1a, 1b, 2a, etc.).

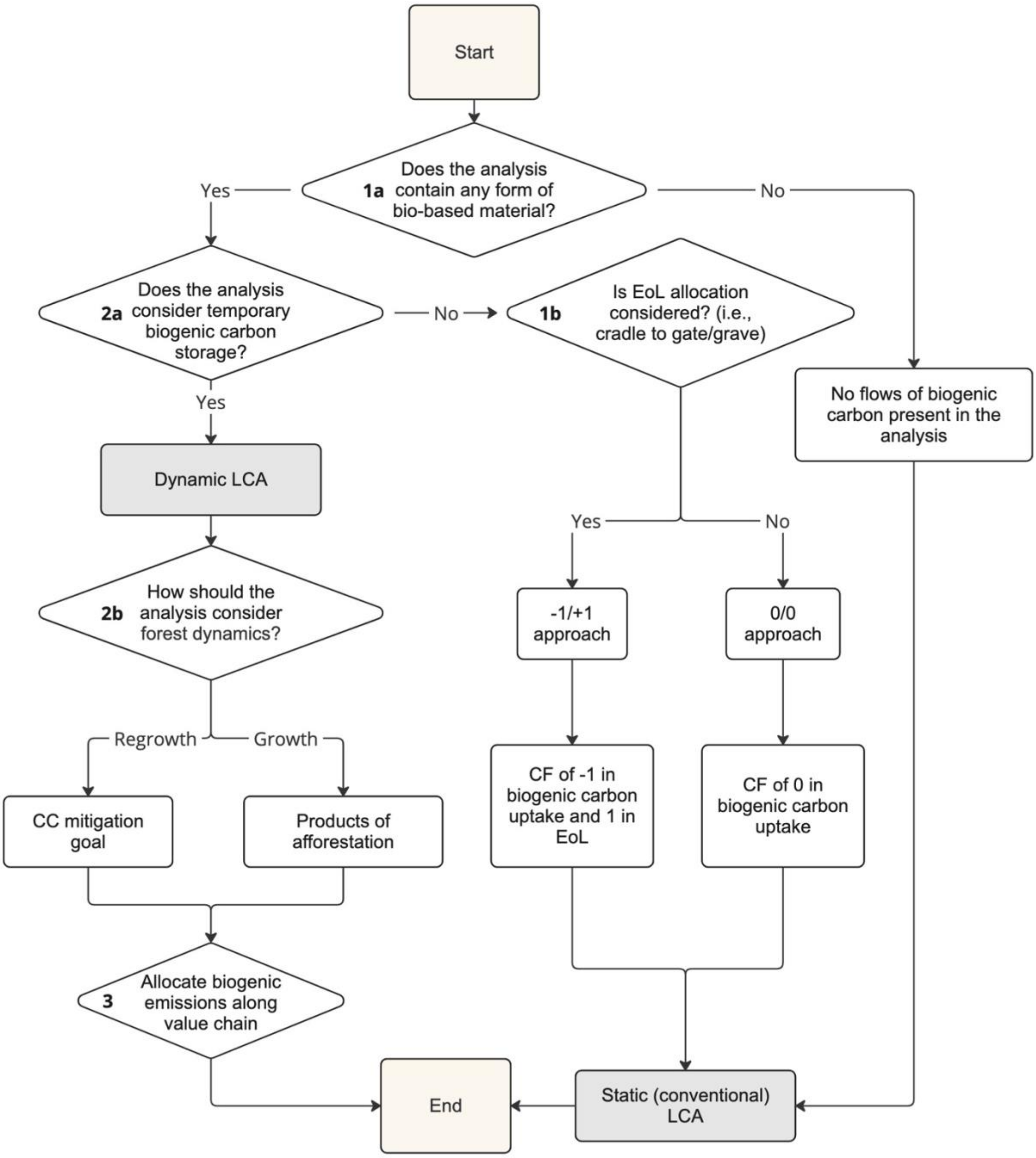


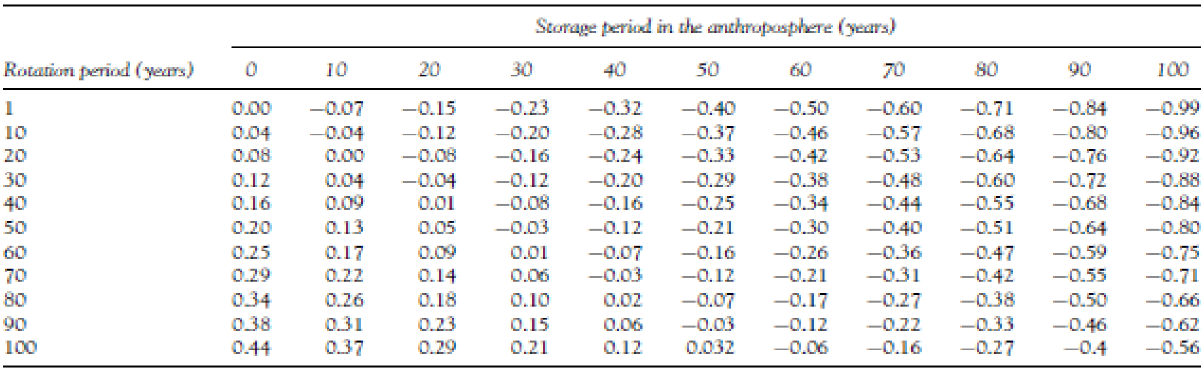
Figure 9: Decision tree for biogenic carbon accounting in LCA, based on the results of the systematic review

3.3. GWP-bio index

Since the vast majority follow the carbon neutrality principle for reasons of complexity, the purpose of the decision tree of Figure 9 is to visualize the current problems of existing biogenic carbon accounting practices (from the systematic review) and to propose a harmonized path that LCA practitioners should follow to minimize the impact of these problems. At the same time, the structure of the decision tree naturally guides the narrative flow of the literature review, thus synchronizing the results of both. Since dynamic modeling is preferred for biogenic carbon, this part requires a bit more explanation on how to integrate these time-dependent factors.

The dynamic modeling of biogenic carbon in the LCA takes place on the left side of the decision tree model, where the key decision is how to account for temporary carbon storage in bio-based materials. Since the focus of this study is on the use of bio-based materials in construction to reduce global CO_2 emissions and mitigate climate change, the *regrowth* scenario is the preferred option (Levasseur et al., 2013). For this scenario, it is recommended to integrate the GWP-bio index from Guest et al. (2013). As explained before, this index depends on three parameters: storage period, rotation period and time horizon, where in this study a time horizon of 100 years is assumed, as recommended in the latest IPCC report (Pörtner et al., 2022). The CFs associated with this time horizon are shown in Table 1 below. The differences in these values are due to the combination of the rotation period and the storage period in the anthroposphere, both expressed in years.

Table 1: GWP-bio factor values for a 100-year time horizon from Guest et al. (2013)



	Storage period in the anthroposphere (years)										
Rotation period (years)	0	10	20	30	40	50	60	70	80	90	100
1	0.00	−0.07	−0.15	−0.23	−0.32	−0.40	−0.50	−0.60	−0.71	−0.84	−0.99
10	0.04	−0.04	−0.12	−0.20	−0.28	−0.37	−0.46	−0.57	−0.68	−0.80	−0.96
20	0.08	0.00	−0.08	−0.16	−0.24	−0.33	−0.42	−0.53	−0.64	−0.76	−0.92
30	0.12	0.04	−0.04	−0.12	−0.20	−0.29	−0.38	−0.48	−0.60	−0.72	−0.88
40	0.16	0.09	0.01	−0.08	−0.16	−0.25	−0.34	−0.44	−0.55	−0.68	−0.84
50	0.20	0.13	0.05	−0.03	−0.12	−0.21	−0.30	−0.40	−0.51	−0.64	−0.80
60	0.25	0.17	0.09	0.01	−0.07	−0.16	−0.26	−0.36	−0.47	−0.59	−0.75
70	0.29	0.22	0.14	0.06	−0.03	−0.12	−0.21	−0.31	−0.42	−0.55	−0.71
80	0.34	0.26	0.18	0.10	0.02	−0.07	−0.17	−0.27	−0.38	−0.50	−0.66
90	0.38	0.31	0.23	0.15	0.06	−0.03	−0.12	−0.22	−0.33	−0.46	−0.62
100	0.44	0.37	0.29	0.21	0.12	0.032	−0.06	−0.16	−0.27	−0.4	−0.56

By blindly following the guidelines of LCA standards and choosing the right-hand side of the model, some papers argued that methods for incorporating time-dependent biogenic carbon flows require too complex analyses (Dodoo et al., 2022; Piccardo & Gustavsson, 2021). Although somewhat outdated, the GWP-bio index could provide a relatively accurate prediction of carbon storage in a wood product in a rather simple way. Therefore, the main argument for using it in this scenario of the decision tree is based on its simplicity and applicability. The GWP-bio index could potentially be easily integrated into LCA software, depending on manual user inputs for the rotation period of the wood species and the service life of the building. The CF for this specific combination would be generated and multiplied by the carbon sequestration of the building according to EN 16449. By adding a GWP-bio factor to the other CFs in the GWP100 impact category based on Table 1, the temporary storage of biogenic carbon is integrated in a simple, yet efficient and clear way.

However, the results using the GWP-bio index should be interpreted with caution, while the reliability of this GWP-bio index is somewhat questionable. The method developed by Guest and colleagues (2013) is probably easier to apply in practice, but a more extended and comprehensive analysis method is generally more accurate and therefore preferable. In addition, the manual entry of a storage period and rotation period could also increase the risk of a greenwashing effect. This is because the practitioner may choose the most advantageous values for the given parameters and thus generate a GWP score that is significantly lower than in reality. A mandatory justification for the input of these numbers could be one way to solve this problem, although it would not lead to 100% reliability of the method. However, since the harmonization process is based on facilitating the decision-making process for biogenic carbon accounting, the GWP-bio approach remains the preferred method for LCA at this time. In the next chapter, a simplified LCA of a case study building in Rotterdam, the Netherlands, is set up and carried out. In this LCA, the decision tree model will be tested for feasibility and usefulness, and the results will show what the difference in GWP values would be based on the chosen pathway.

4. LCA case study

4.1. Methodology

The findings out of the existing literature and systematic review have opened a way for a possible new framework that aims to bring consensus to the biogenic carbon accounting in bio-based materials. In this chapter, the decision tree model that was formulated will be assessed through a simple LCA case study with the aim to answer the following question:

- *To what extent do the different accounting methods lead to alternative GWP scores for the CLT case study building "SAWA" in Rotterdam?*

Since this specific sub-question essentially covers the effect of the difference in environmental impact results, a Life Cycle Assessment (LCA) is the most suited method to answer this. The LCA will be conducted according to the guidelines of ISO 14040 and 14044 (ISO, 2017) and the LCA Handbook (Guinee, 2002). This means that all four stages that are part of a LCA will be included, as visualized in Figure 10. In terms of impact assessment, a complete LCA currently includes 19 impact categories according to the updated version of 2019. While this study focuses solely on the issues of accounting for biogenic carbon, the only relevant impact category is climate change with the GWP100 indicator, including its subcategories GWP-fossil and GWP-biogenic. This LCA will use the different versions of (v3.1 and the v3.1 EN15804) of the Environmental Footprint reference packages (EU Commission, n.d.), as these are considered to be the closest to the updated European standards and therefore useful for comparing different approaches.

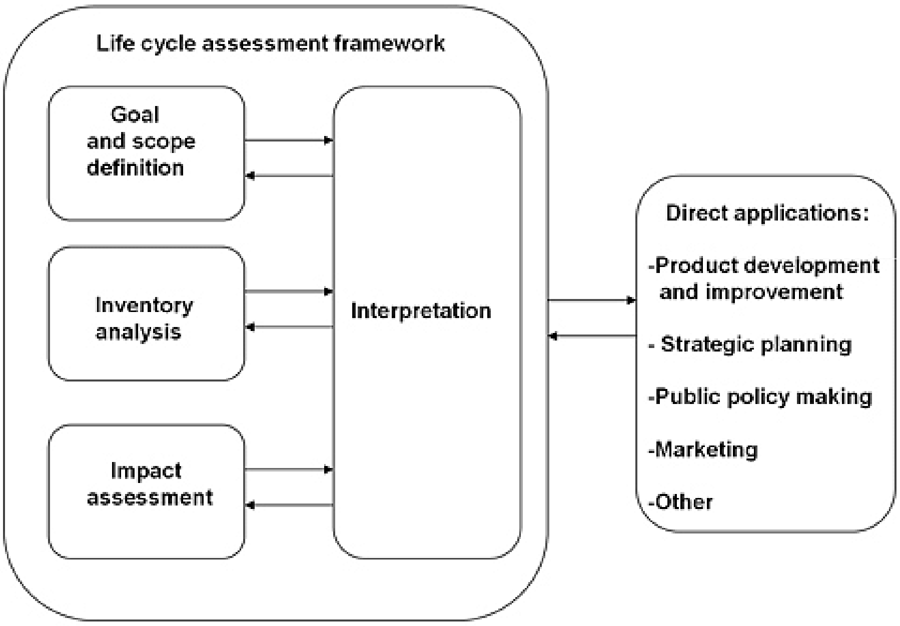


Figure 10: The four stages of an LCA according to the ISO 14040 (ISO, 2017).

Brightway is used as the base program for this research, which is an open source software for LCA calculations in the Python programming language (Mutel, 2017). Activity Browser is a software that can be used within this program and is designed to create a simplified and more user-friendly LCA variant for those who are not familiar with programming (Steubing et al., 2020). As the aim of the study is mainly to focus on the methodological issues and does not require a complete and complicated LCA, Activity Browser is considered suitable for this study. The ability to create and compare different scenarios was also a reason for choosing this software. The data is taken from the biosphere database included in the software, where the ecoinvent cutoff database version 3.9.1 (ecoinvent, n.d.) was provided by Leiden University. The results of the Global Warming Potential (GWP) impact assessment are presented in the results section, where their interpretation follows in the discussion.

4.1.1. Case study selection

The LCA is carried out on the case building project “SAWA” in Rotterdam (Figure 11). The building was designed by Mei Architects and Planners and commissioned by NICE Developers and ERA Contour, all based in Rotterdam. The building is constructed almost entirely of CLT, with minimal use of concrete (Welch, 2023). Prior to the start of construction of this building in late 2022, the project was voted the Popular Choice winner of the 2023 Architizer A+ Sustainability Award and won the Paris Design Award in the Green Architecture category. The project will be the country's first 50-meter circular residential building made of wood. Furthermore, it is positioned as the promising ‘healthiest building in the Netherlands’ and can be seen as an interesting case to investigate the actual environmental performance of (Welch, 2023). However, the reasoning behind the selection of this building is not based on these rankings and promises, but rather on the future construction of Dutch cities.

Figure 11: The design of “SAWA”. Retrieved from https://mei-arch.eu/projecten/sawa/ on 17-04-2024.

Future housing development is an important issue, where the Netherlands had got to cope with a relatively high population growth over the last years. At the end of 2023, the country registered a population of more than 17.9 million people and is expected to have 18.5 million inhabitants in 2030 (CBS, 2024). The current housing shortage is due to these numbers and is only expected to increase in the coming years to 390000 houses in 2030 (NOS, 2024). In order to cope with this increasing housing shortage, an additional 88000 dwellings were added in 2023. However, this still does not seem to be enough, as the Dutch government wants an annual increase of 115000 houses to cover the expected population growth (NOS, 2024). As this number is not expected to be reached, it is of high importance that the building sector needs a more efficient and sustainable development process. In addition to regulatory protocols and the sustainable use of materials, this includes rapid construction methods such as the use of prefabricated elements.

Since not all housing types can be evaluated in this study, “SAWA” was chosen because it fits the current trends of high-rise construction in cities such as Rotterdam. High-rise buildings have been cited as an efficient way to increase density from an urban planner’s perspective (Rechkemmer, 2023). It also benefits walkability, limits urban sprawl and the disappearance of suburban green spaces. High-rise structures in the form of mass timber have also been studied and found to be efficient in reducing greenhouse gas emissions (Skullestad et al., 2016). “SAWA” will add 109 residential units (mixed size and rental), and thus this type of housing contributes to the shortage by covering a relatively small area of land. The building also has 15 floors and a total gross floor area of 12000 m2 (8710 m2 net).

4.1.2. Goal & scope definition

Goal

The main objective of this LCA is to test the feasibility and usefulness of the decision tree model from the previous chapter. In doing so, it will discover and compare the different results depending on the methodological choices in accounting for biogenic carbon in a specific case study. As mentioned, it is part of a master’s thesis research project focused on this specific topic, where LCA is ultimately used as a means to answer the research question. Since the topic of the study and the decision tree model concerns the accounting of biogenic carbon, a simplified form of LCA will suffice for this methodological part. This simplification means that the study will focus only on the main load-bearing structure of the building. In this way, the differences in environmental impact can be estimated without having to collect huge amounts of data for the whole building.

Scope

The research objective for the LCA is specifically focused on a single building in the Netherlands and is carried out to analyze the impact of the different methodologies used to account for biogenic carbon. As a result of the simplified form of this analysis, there are certain scopes that need to fit within this objective and will be elaborated on. All wood elements (CLT and glulam) come from the German manufacturing company Derix. The EPD for their product X-LAM can be found on their website, which contains a lot of information relevant to the following scope definitions (Derix, n.d.).

Geographical

The geographical scope chosen in the LCA software varies between global, Rest of the World (RoW) or European data. Since the LCA is studying a building in the Netherlands, specifically the city of Rotterdam, the geographical scope will aim to include processes and activities that are as similar and close as possible. This means that it will gather the most recent data from the ecoinvent database and use the processes that either occur in the Netherlands or have a similar proximity. The mass timber products used in the building come from a forest in Germany, while the Derix production site for the panels is located in Niederkrüchten. The distance from this location to Lloydpier in Rotterdam (future "SAWA" location) is 179 km, which is further calculated in ton kilometers. The remaining transport emissions are automatically calculated from market averages in the ecoinvent database, which differ between RER (Region of Europe), GLO (Global) and Europe excluding Switzerland (ecoinvent, n.d.). For concrete and steel components, national averages of 50 kilometers were used.

Temporal

In order to effectively test the different biogenic carbon accounting approaches, it is very important to set the temporal scope accurately. The software and impact categories used for the assessment do not include forest dynamics, which means that this has to be added manually by the user. According to the literature, the formulation of these temporal aspects depends on three main factors: the time horizon of the GWP100 impact indicator, the storage period of the material, and the rotation period of the forest (Guest et al., 2013).

First, the standard time horizon of calculating the environmental impact for Dutch buildings is 75 years (NMD, 2022). Since the CFs from the GWP-bio index are calculated for whole decades, the storage period for the biogenic carbon in the wood is rounded up to 80 years. For this reason, the reference service life (RSL) of the case study building is set to 80 years to simplify the dynamic modeling processes. According to Derix, the RSL of their CLT and glulam components is consistent with the service life of the building as long as the materials are used as intended. Their EPD assumed an RSL of 100 years, so both 80 and 100 years are considered for the storage period (Derix, n.d.). For simplicity, all building materials are assumed to have the same reference life as the building.

The time horizon for calculating the climate change impact (GWP) is usually set to 100 years, which is in line with the latest published IPCC report (Pörtner et al., 2022). As mentioned in the literature, this number only represents the horizon over which the radiative forcing is considered. The wood species used for the production of CLT is German spruce (C24), where these forests are known to have a rotation period between 80 and 100 years (Völkl, 2022). Since this rotation period is a highly influential variable in the accounting methods, this study will additionally test the sensitivity of this variable and use rotation periods of both 80 and 100 years. The three different conditions are shown in Table 2, which together produce specific results for the GWP-bio index, as shown in the scenario presented later in the report.

Table 2: Three (varying) temporal factors.

Conditions	***Input LCA***
Time horizon	100 years
Storage period	80 and 100 years
Rotation period	80 and 100 years

Technical

As mentioned above, the purpose of this case study is to test the feasibility of the decision tree and to show the difference in GWP results between dynamic and static LCA modeling in a real-life scenario. This real-life scenario will therefore only include the main structural parts of the building and will not be as detailed as the majority of building LCAs. The figures in Table X represent the quantities used to construct the main load-bearing structure, with the materials used being concrete, reinforcing steel, and mass timber (both CLT and glulam). The quantities are not differentiated between the different structural components (walls, floors, etc.), so an analysis of their impact is not within the scope of this study.

System boundaries

As the focus is on the accounting of biogenic carbon, it is not necessary to include all the different life cycle stages of the case study building as defined by EN 15978 (CEN, 2011). Referring back to Figure 6 in the introduction, the life cycle of a building is divided into four main modules. The pre-construction carbon uptake is shown as a negative number in Module A and the release as a positive number in Module C in the static methods mentioned, which leads to misleading results when evaluating these two modules separately (Hoxha et al., 2020). For this reason, these two modules are treated together in this study. However, since the installation/construction (A5) and demolition (C1) processes are expected to be almost identical due to the use of prefabricated mass timber panels, they are omitted from this case study for the sake of simplicity (Derix, n.d.).

On the other hand, this study does not consider all phases within the use phase. The wood products do not require any renovation or maintenance (B2 to B5) during their life in the building, while the operational energy and water use (modules B6 and B7) do not depend on the way biogenic carbon is considered in the LCA and can therefore all be neglected in this study. The benefits of Module D are also not included because of the many uncertainties in this part of the building's life cycle. In summary, this LCA will follow a cradle-to-grave approach, with the exception of modules A5, B2-B7, C1 and D, as shown schematically in Figure 12 below.

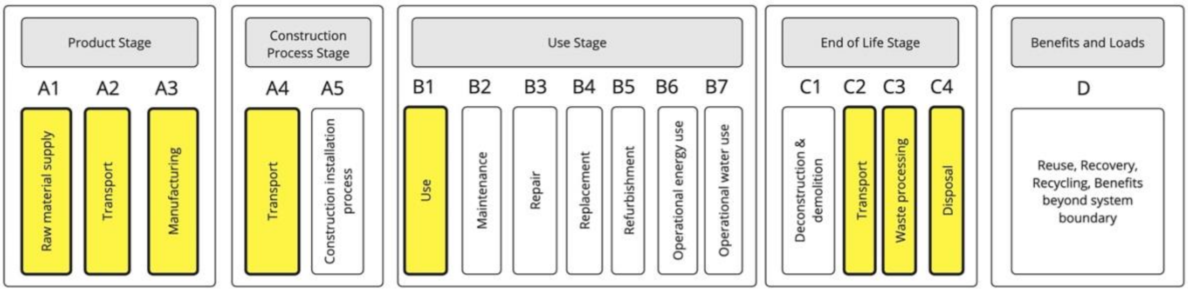


Figure 12: System boundaries of the assessed life cycle stages in the study, visualized in the overview of the EN 15978 (CEN, 2011). The yellow boxes show what is covered in the analysis.

The product stage (A1-A3) considers the production of the three types of materials for the main supporting structure of "SAWA", including the extraction and processing of raw materials, transportation to the manufacturing site, and the energy required for these processes. The construction stage (A4) consists only of transportation from the product manufacturer to the construction site. The use stage (B1) is where the uptake and some of the modeling of biogenic carbon takes place. The end-of-life processes (C2-C4) start with the transport from the demolition site to the sorting and then to the disposal site. There, depending on the material, it is either incinerated, recycled or landfilled. For steel and concrete, regional market averages were used.

Functional Unit

Since the aim of the LCA is to find the methodological differences in dynamic and static modelling in terms of biogenic carbon, the functional unit of this study is *1 m2 gross floor area of the main supporting structure of "SAWA" for an RSL of 80 years.*

Scenarios

The case study is tested on the basis of several scenarios, which are based on the different temporal scope decisions. They differ in terms of LCA method (static or dynamic), reference period, rotation period and associated GWP-bio value, as shown in Table 3. Only the *regrowth* scenario is included in the GWP-bio index, as mentioned in the previous chapter, where it was also explained how the values per scenario are derived.

Table 3: Scenarios for the LCA case study.

Scenario	***Method***	***Reference (storage) period***	***Rotation period***	***GWP-bio***	***Forest system***
0/0	Static LCA	80 years	-	-	-
-1/+1	Static LCA	80 years	-	-	-
$D_{80/80}$	Dynamic LCA	80 years	80 years	-0.38	Regrowth
$D_{80/100}$	Dynamic LCA	80 years	100 years	-0.27	Regrowth
$D_{100/80}$	Dynamic LCA	100 years	80 years	-0.66	Regrowth
$D_{100/100}$	Dynamic LCA	100 years	100 years	-0.56	Regrowth

The Activity Browser software includes several versions of the Environmental Footprint (EF) reference packages. The most recent updated version is version 3.1, with two additional variations; the EF v3.1 and the EF v3.1 EN15804. Both include all three different impact categories for climate change: fossil, biogenic and luluc (land use and land use change). This study will focus on the first two, including the overall climate change impact indicator. The EN15804 variant differs for the CFs of biogenic CO_2 uptake and emissions, which maintain the -1/+1 approach similar to the updated standards. These two impact categories are used for the static LCA scenarios. For the dynamic scenarios, the temporary biogenic carbon is modeled by the CFs of the GWP-bio indicator. The biosphere flux 'carbon dioxide, in air' ('natural resource') was added to a new activity containing the initial carbon storage quantities for each scenario. The flow was then multiplied by the CFs from each combination of rotation and storage period, resulting in the total CO_2-eq storage.

4.1.3. Life cycle inventory

The primary data for this case study comes from the architectural firm that designed "SAWA", Mei Architects and Planners. This will consist of quantitative data, specifically the quantities of CLT, steel and concrete from the main structure of the building. In addition to the figures provided by Mei Architects and Planners, the ecoinvent database was used to find the background processes associated with the material production. Table 4 below shows the Bill of Materials (BOM) resulting from the final design of "SAWA". An additional amount of 3% was added to account for assumed losses during construction (Derix, n.d.). Transportation inputs were calculated using Google Maps and then multiplied by the weight of the products. For the EoL scenarios for concrete and steel, the regional market average for waste products was used, while the model assumed a 100% municipal incineration scenario for waste wood. More information on the exact input flows, including assumptions, can be found in Appendix B.

Table 4: Bills of materials (net, without accounting for losses during construction)

Components/material	***Quantity [m^3]***	***Weight [kg]***	***Weight [tons]***
CLT floors	2100,96	997535,808	997,53
CLT walls	128,37	60950,076	60,95
Glulam columns	439,23	208546,404	208,546404
Glulam beams	651,67	309412,916	309,412916
Total timber	3320,23	1576445,2	1576,45
Steel	30	235,5	0,2355
Total steel	30	235,5	0,2355
Concrete	2151,82	5164368	5164,37
Total concrete	2151,82	5164368	5164,37
Grand total	5502,05	6741048,7	6741,0487

4.1.4. Sensitivity analysis

Since the results for the different rotation and storage periods have not yet been tested in the scenario modeling, the way the carbon sequestration was calculated could also change the final results. The figure used in the default model was 759 kg of CO_2 sequestered per cubic meter, which was based on figures provided by Mei Architect and Derix's EPD for the wood product (Derix, n.d.). However, another EPD for Derix's wood product reported a biogenic carbon uptake of 769.3 kg. This relatively small difference of about 10 kg/m^3 could lead to larger differences when applying the GWP-bio index to the full volume of the building.

The European standard's calculation tool is found in EN 16440 and is based on parameters such as the density and moisture content of the wood (CEN, 2014). The moisture content is often set at 12% for wood products in this formula, where the density also depends on this value. For the spruce product for “SAWA”, the density is 470 kg/m^3 at a moisture content of 12%, while it is 413.6 kg/m^3 at a moisture content of 0% (Derix, n.d.). The EN 16440 calculation method uses a variable parameter where the practitioner can choose the moisture content at which to set the density. Some other forms of this calculation from Dutch websites take either the dry mass or another moisture content of the wood (Centrum Hout, n.d.; Hout geeft zuurstof, n.d.). In addition, the formulas within these methods are not completely similar and could therefore potentially cause significant differences in the final results. The results of the most relevant methods found for the carbon storage of “SAWA” building products are given in the sensitivity analysis after the primary impact results.

4.2. Case study results

4.2.1. Impact assessment

The results at the midpoint level of the different GWP100 (sub)categories are presented in Figure 13 and show the results for the mass timber case study building “SAWA”. The two static approaches produced a similar impact of 107 kg CO_2-eq/m^2, with the -1/+1 method showing the additional biogenic CO_2 emissions without distracting from the overall GWP category. The four dynamic scenarios each produced lower results compared to the static methods, with the $D_{100/80}$ and $D_{100/100}$ producing negative values for CO_2-eq emissions, indicating net storage over their lifetimes. The former resulted in the lowest GWP value of -43 kg CO_2-eq/m^2. This is a difference of 150 kg CO_2-eq/m^2 (140%) from the static approaches, where the highest scoring dynamic scenario ($D_{80/100}$) produced a GWP score of CO_2-eq/m^2.

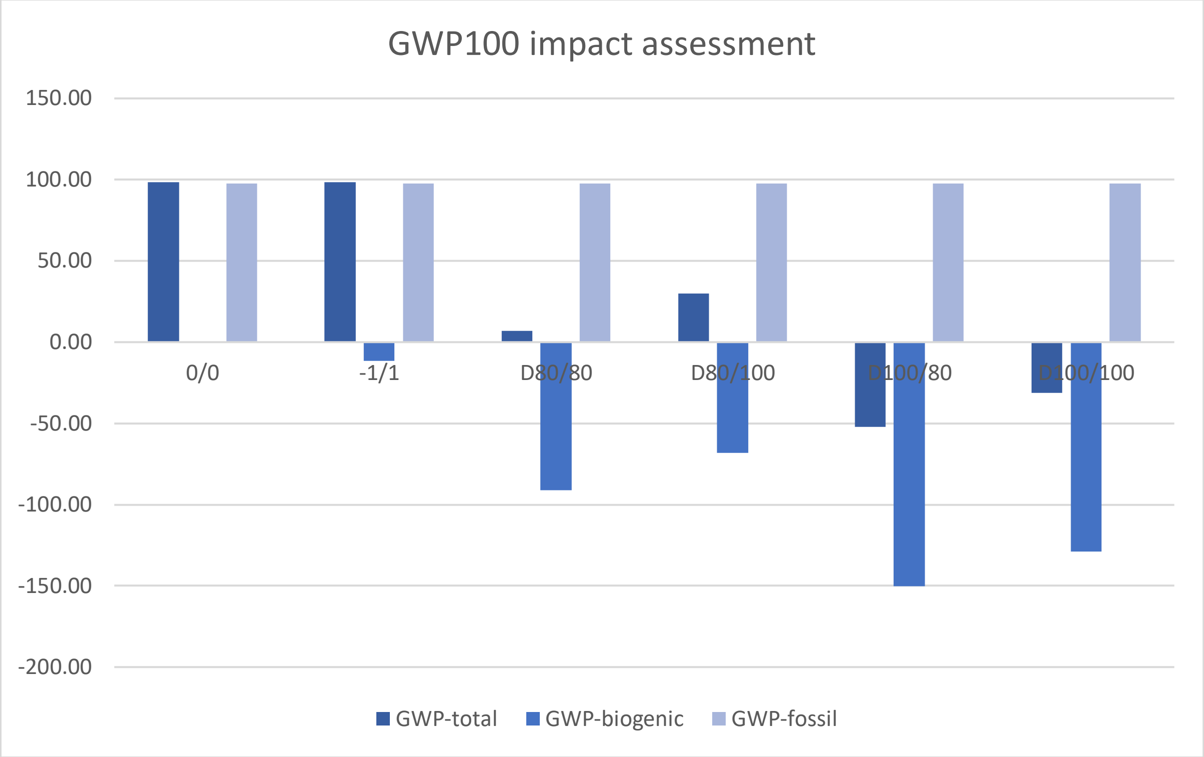


Figure 13: Overview of generated GWP100-scores for the “SAWA” building among the different scenarios by the Activity Browser software.

The subcategories illustrate the main findings of this study. Since biogenic emissions are considered non-fossil, the GWP-fossil is not affected by the temporal effects and therefore results in the same value for this subcategory across all scenarios (107 kg CO_2-eq/m^2). Next, the GWP-biogenic is where the temporary biogenic carbon storage is modeled. It is noteworthy that this subcategory produces a value of 0.25 CO_2-eq/m^2 in the 0/0 approach. This amount is solely due to biogenic CH_4 emissions, which, unlike CO_2 emissions, are included in the EF v3.1 subcategory. The overall impact indicator GWP100 for climate change depends on the sum of the subcategories. Only the -1/1 approach differs from this rule, as the biogenic GWP does not count towards the total impact GWP100.

As shown in Figure 13, the scenario with the lowest total GWP result is coupled with the shortest rotation and the longest storage period. This is the result of multiplication with the corresponding GWP-bio value. Table 5 illustrates how the initial biogenic carbon storage (759 kg CO_2/m^3 provided by Derix and Mei Architects) for the “SAWA” building was converted to the total storage for each scenario. In addition, the stored CO_2 is shown as values per year.

Table 5: Final carbon storage numbers used as input for the LCA model, varying per scenario.

Scenarios	$D_{80/80}$	$D_{80/100}$	$D_{100/80}$	$D_{100/100}$
Initial carbon storage (kg)	2520054,57	2520054,57	2520054,57	2520054,57
Storage period (years)	80	80	100	100
Rotation period (years)	80	100	80	100
GWP-bio	-0,38	-0,27	-0,66	-0,56
Total CO_2-eq storage (kg)	-957620,74	-680414,73	-1663236	-1411230,6
Total CO_2-eq storage (kg/m^2-year)	-0,9975216	-0,7087653	-1,38603	-1,1760255

Figure 14 is a visual representation of the effect of this carbon storage per square meter relative to an RSL of 80 years, showing the differences between the 80- and 100-year rotation periods of the forests. The most striking thing about this graph is that for a 100-year rotation, the carbon storage effect on the atmosphere becomes positive only after a storage period of 53 years. With a rotation period of 80 years, the amount of carbon stored per square meter-year is -1.00 kg CO_2-eq for the 80-year rotation period and -0.71 kg CO_2-eq for the 100-year rotation period. This is a rough difference of 0.29 between the two rotation periods for his predicted RSL.

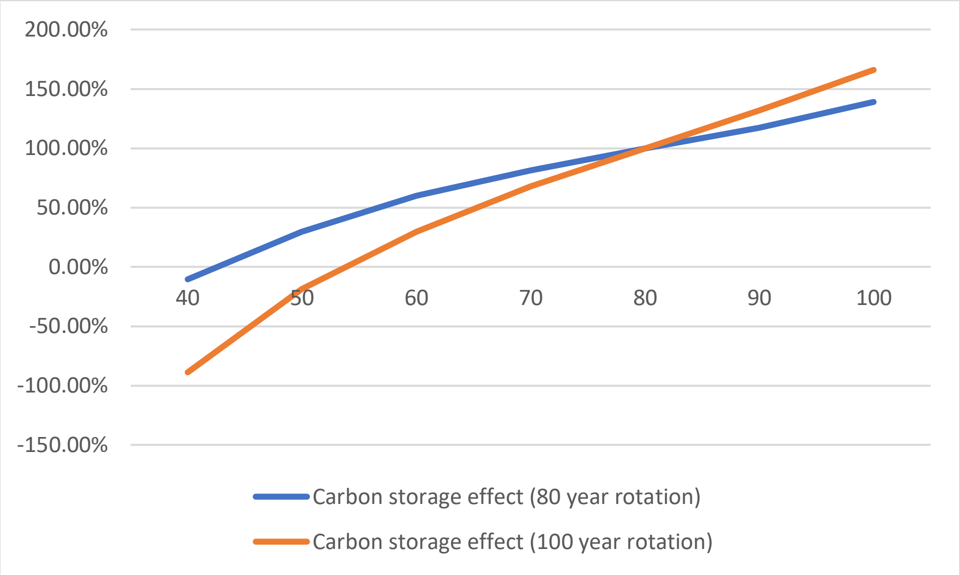


Figure 14: Carbon storage impact per year of use for the carbon storage of "SAWA" relative to a RSL of 80 years. The two rotation periods (80 and 100 year) are compared to each other for buildings lifespans from 40 till 100 years.

4.2.2. Sensitivity analysis

The sensitivity analysis shows several differences between the investigated calculation methods (Figure 15). The "Centrum Hout" formula resulted in the highest number of hypothetical 2557 tons of carbon sequestered in the "SAWA" building. Of the six figures evaluated, two assumed a standard moisture content of 12% (+- 2), whereas the 'Hout geeft zuurstof' formula included a density at 0% moisture content for the spruce product. The EN 16449 method could be evaluated with both moisture contents and showed a difference of 37 tons of sequestered carbon in the final construction of "SAWA". The results with 0% moisture content were all significantly lower than those with 12% moisture content. This indicates that the results are quite sensitive to the method used to calculate carbon storage, particularly with respect to the moisture content chosen. For this study, however, the second lowest was used in the default model of the LCA (759 kg/m^3 from the Derix EPD).

Figure 15: Visualization of the various calculation methods for carbon sequestration per cubic meter of wood product. The different colors represent at what moisture content the calculations were executed.

5. Discussion

This section discusses the most important results with its accompanied interpretations, including the benefits and issues of using the GWP-bio approach in LCA and its relevance to the research gap of the study. After that, the most important limitations and uncertainties of the research design are reviewed.

5.1. Interpretation of results

The main research question of this study was to assess the impact of different biogenic carbon accounting methodologies in the LCA of bio-based materials, specifically mass timber. In order to obtain the most relevant results, the methodology was divided into two main parts. The first part consisted of a thorough systematic review of the available literature on the topic, classifying and analyzing it based on specific biogenic carbon accounting practices. This review led to several interesting observations that formed the basis for the rest of the study.

Existing LCA studies of case buildings have shown that the GWP results of bio-based materials are strongly influenced by the practitioner's approach to biogenic carbon accounting. Here, the majority of the systematically reviewed studies decided that dynamic modeling would require too complex an analysis and therefore treated biogenic carbon under the principle of carbon neutrality. Among the static approaches, as expected, the authors more often followed the European standards updated in 2019 and mentioned the amounts and flows of biogenic carbon in their study using the -1/+1 method (CEN, 2019). The 0/0 method does not mention biogenic carbon flows, which was found in 12 of the 33 studies. However, both approaches do not take into account the benefits of temporary carbon storage during the lifetime of the biobased product, and it seems that this dynamic modeling is very underused in LCA. In addition, a significant number of studies did not specify how they modeled biogenic carbon in their LCA, including some that did not even mention the concept.

Some studies have based their calculations of biogenic carbon on a different perspective, using the temporal consideration from Levasseur et al. (2010). Although Hoxha et al. (2020) found an increase in the impact score with the dynamic approach, they concluded that this method is the most transparent and reliable to use in LCA, while also suggesting a mandatory end-of-life consideration when using the static approaches. J. H. Andersen et al. (2022) and Hellmeister (2022) also included temporary biogenic carbon storage based on forest regrowth assumptions in their studies and found a reduction in final GWP scores. Several other studies found favorable results due to biogenic carbon by accounting for a negative credit to GWP based on Module D benefits, such as reuse or avoided fossil fuel use (Kwok et al., 2019). Despite the fact that a proper allocation of this EoL can potentially reduce impacts, it makes comparisons between LCAs ambiguous when considering different approaches to biogenic CO_2 (Garcia et al., 2020). Therefore, Garcia and its colleagues advised to allocate the temporary storage benefits of biogenic carbon during its storage (in Module B) rather than overcomplicating the issues at the end of its life cycle.

The results of the systematic review led to the formulation of a decision tree model. Three main criteria formed the basis of this model: the presence of biogenic carbon in the biomass of the material, temporal factors/forest dynamics, and end-of-life (EoL) allocation. The primary purpose of the decision tree was to systematically set up the LCA case study, in which the differences in pathway choice would be quantified in the terms of GWP results. Each decision node in the framework leads to either staying with the dynamic method or taking the static approach, similar to many of the studies from the systematic review. By testing the impact of the modeling choices throughout the decision tree framework, a form of consensus on how to account for biogenic carbon in LCA could be initiated.

In the case study, three main methods were used to test the differences in outcomes based on the path taken in the decision tree. These were the 0/0, -1/+1 and dynamic (*regrowth*) methods, with the latter incorporating multiple scenarios in its temporal characteristics with the GWP-bio approach. The results showed significant reductions in GWP100 results for the GWP-bio approach with forest regrowth compared to the static methods within the same assessment. Based on the European guidelines maintained in the current LCA, the main supporting structure of "SAWA" was calculated to have an impact of 107 kg CO_2-eq/m^2 based on an expected RSL of 80 years. Although this static approach accounted for several biogenic carbon emissions (both CH_4 and CO_2), it did not affect the final impact of the building. By applying the GWP-bio index from Guest et al. (2013) and assuming forest regrowth, the ratio of GWP-fossil/GWP-biogenic shifted due to the increase of carbon storage. This led to the GWP-total impact being significantly reduced to a range of 39 to -43 kg CO_2-eq/m^2, depending on the scenario for each of the estimated rotation and storage periods.

The main finding of the case study is that temporary biogenic carbon storage, which is often neglected in LCA studies due to international and European guidelines, can have a significant impact on the environmental impact results. In the "SAWA" case study, the results show a decrease for dynamic approaches, which is mainly due to the consideration of forest regrowth with a sufficiently low rotation period. The different scenarios have shown that rotation and storage periods are highly influential variables; if a decrease in rotation period is paired with an increase in storage period, the total amount of stored carbon increases. The case study also assumed a 100% incineration scenario for the wood products, which is not the preferred EoL allocation according to circular economy principles. In the LCA case study, biogenic carbon benefits of reuse or avoided fossil fuel use are not present, demonstrating that the storage of "SAWA" is the least minimum reduction that mass timber can provide in a building. In a full circular economy scenario, the CLT and glulam panels are reused and most likely increase the storage capacity of mass timber products and further reduce the GWP values.

5.1.1. GWP-bio proposal

The case study has applied the decision tree model by testing the three different biogenic carbon accounting methods. It has primarily shown that, under the right conditions, including the forest dynamics (for example through the GWP-bio index) for biogenic carbon accounting in LCA is the preferred pathway choice inside the model. By not taking temporary carbon storage into consideration, the final GWP result can end up being vastly different and sketch an unrealistic view of the environmental impact of mass timber constructions. For cases in which the consideration of forest dynamics is not possible, it is found that the -1/+1 method often provides misleading results, especially when the EoL stage (Module C) is not included (Hoxha et al., 2020). For the reason of neutralizing the allocation issues for biogenic carbon in the static method, it is not recommended to change any of the CFs in the impact categories concerning biogenic carbon (Frischknecht, 2010). Yet, this method does not link rotation periods with the storage periods and therefore not portray the building's performance in a correct way.

The GWP-bio approach is one of the methods that includes forest dynamics in a specific manner. Besides having highlighted the advantages of using it, there are also arguments why this might not be the most reliable method for the dynamic modelling of biogenic carbon. The most critical one of implementing this approach in LCA concerns the risk of greenwashing. The case study of this paper has shown that within the same method, there are large differences in results dependent on the chosen rotation and/or storage period. Choosing the correct CF for the GWP-bio approach is at the moment directly the action of the LCA practitioner and can therefore cause implications where the study uses more advantageous numbers for their calculations. This greenwashing risk is difficult to entirely eliminate within the approach, but the effects could be minimized through the following two steps.

There are several actions which can increase the reliability of the GWP-bio index, in which the rotation period is the first uncertain factor. Currently, the EPD from a specific wood product includes various information such as the wood species, biogenic carbon content and expected service life (CEN, 2019). This information is reviewed and verified by third parties and complies with the updated European standards for LCA. Adding the average rotation period of the forest species could become mandatory for wood products, hereby setting a strict number that can be used in the calculations. In order to do this, standardization organizations should include this in their standards and secure more complete EPDs of wood products. The exact rotation period is often hard to determine, but usually it is possible to give an indication. From this indication (usually expressed in a range of +- 10 years), the LCA practitioner can decide to either take the average number, or express both the minimum and maximum rotation period in the assessment.

Second, the results of the LCA should explicitly be limited to the service life of the building. In the second phase of conducting an LCA, the inventory analysis includes the establishment of scope definitions and functional unit. These usually contain temporal boundaries that sets a specific RSL. When the RSL of the building is for example set at 100 years, the GWP-scores generated for this building will include the GWP-bio based on a 100-year storage period and therefore can only be valid for this horizon. The service life is however, similarly to the rotation period of the forest, a rather difficult prediction. When a reuse scenario is assumed, the storage period is extended and could therefore be argued that also the GWP-bio changes according. Alternatively, the LCA can be composed of multiple scenarios in which the RSL differ based on EoL scenarios. For this to be realized, the GWP-bio factors should aside from a general revision also include storage periods for more than 100 years.

With these steps the risk for greenwashing is reduced, but not entirely taken out of the analysis. The main disadvantage of the GWP-bio index is that the calculation is done with one final number that is based on (only) two independent variables. Dynamic modeling was repeatedly cited as a more complex process (J. H. Andersen et al., 2022; Garcia et al., 2020; Hoxha et al., 2020), where it instead takes the emissions from each point in time and subsequently calculates how much effect this has on the climate. In a certain way, the GWP-bio is a simplified version of this, without giving the practitioner the necessity to conduct complex and comprehensive analyses. The only barrier to opt for a dynamic model in LCA seems to be this complexity and the uncertainty of how to accurately implement it. This accuracy is still rather questionable with the GWP-bio index, since they are still an estimate of the impact of CO_2 emissions under the right circumstances (C. E. Andersen et al., 2024). Despite the limitations of the approach from Guest et al. (2013), a revised and corrected version of the index could provide an uncomplicated and understandable method for beginning to include the regrowth of forests in LCA studies with bio-based materials.

5.1.2. Relevance to research gap

This report began by showing the need for a reduction of the CO_2 emissions for the construction of our built environment and consequently highlighting mass timber as a potential solution for this (Heräjärvi, 2019). Besides its generally lower global warming impact for production and manufacturing processes opposed to concrete and steel (Chen et al., 2022), wooden products can temporary store carbon in its tissues. This reduces radiative forcing for a period, provides more time for technological innovations and can have a significant effect on reducing risks of exceeding short-term environmental tipping points (Brandão et al., 2013). If the regrowth of the forest system is additionally considered, the carbon storage could contribute directly to mitigation of climate change (Levasseur et al., 2010). One important notation for the forest dynamics is that the start of this assessed period will experience a lower amount of carbon uptake from forests, since the growth rate of trees increase with size and age until they start to decline again (J. H. Andersen et al., 2022).

It therefore seems only logical to include the biogenic carbon flows in LCA and make the entire picture of a building's environmental performance complete, especially if we want to reduce the climate change impacts in the construction sector. The results of this study indicated that if the storage period of the wooden product in the construction is sufficiently long, the carbon that is stored in the building and taken up by forest growth will lead to a negative GWP-score. This was also found in other studies that modelled their LCA in this dynamic way (J. H. Andersen et al., 2022; Hellmeister, 2022) and hereby confirms the proposition that this storage should not be neglected.

The problem arises when deciding on the correct approach for modelling biogenic carbon in LCA. A handful of approaches for the treatment of biogenic carbon have been proposed, where Hoxha and its collegeus (2020) presented the most common approaches. These are following the method of the carbon neutral principle, which is based on the assumption that the biogenic carbon follows a 'short' carbon cycle which does not have a significant effect on the global climate (J. H. Andersen et al., 2022). The European and international standards both adhere to his approach and have applied it in the rules for setting up EPD's for construction works due to environmental pressures (CEN, 2019). The issues related to biogenic carbon accounting are also related to the boundary settings for LCA studies and EoL allocation. Garcia and its collegues (2020) have on their turn showed the difficulties on the timing of biogenic emissions, where it was evident that the choices of the practitioner cause highly different results. As a result, they proposed to either allocate biogenic carbon emissions (at EoL) consistently with the accounting method that is used or, for dynamic models, account for the temporary storage advantages of biogenic carbon storage during its storage and not at the end of its lifecycle (Garcia et al., 2020)

Yet, as this study has shown through the systematic review, there is quite a high variability among the utilized approaches in LCA studies and consensus across the LCA methodologies is thus far from reached. A consequence of this is that it is harder to compare the LCA studies to each other, hereby creating a lack of trust in studies that contain bio-based materials (J. H. Andersen et al., 2022). Whereas LCA is typically praised for its useful and fair assessments with application of many sectors (Säynäjoki et al., 2017), the trust is now undermined due to the practitioners approach for handling biogenic carbon. To combat this, a harmonization process between standardization organizations and main actors within this field is necessary.

The decision tree model that was set up based on the existing literature serves as a first start in this development of harmonization. Within the dynamic modelling in LCA, the GWP-bio approach is merely one possibility of calculating the carbon storage for wood products. For reasons of simplicity and applicability, the GWP-bio was chosen as the first approach in this process. Although there will certainly be a more accurate and reliable method for temporary biogenic carbon accounting, this study argues more for the start of harmonization through this decision tree. Besides having set the framework for the case study, the decision tree mostly acts as a consulting tool that can contribute to creating consensus in LCA that contains bio-based materials like mass timber. The most important factor in this is to have the main actors acknowledge the reliability of dynamic modelling with forest regrowth, which will ideally result in a harmonized and ideal approach for future biogenic carbon accounting.

5.2. Limitations and uncertainties

As shown in several chapters throughout the report, the inclusion of temporal aspects in LCA with the GWP-bio index has several uncertainties. Although this research has provided some interesting insights into the research questions, the chosen method and design have certain limitations that could reduce the trustworthiness of the results.

The systematic review was conducted with the aim of identifying differences in the modeling of biogenic carbon in existing LCA studies. A common problem that arises in systematic reviews is the inclusion of publication bias, which is defined as the tendency to only publish studies that show statistically significant results (Siddaway et al., 2019). In this research, all but one (Hellmeister, 2022) were published articles from journals, which to some extent biases the results of the systematic review. The LCA results of bio-based materials mostly showed a lower GWP score than the competitor (i.e. concrete or steel). However, the actual result based on the reviewed papers, the decision tree model, was less affected by this type of bias. This is due to the fact that the model concerned the biogenic carbon modelling specifically, where the papers were analyzed in a neutral way when examining the methodology of the LCAs. Including more unpublished work would therefore most likely not have changed the outcome of the systematic review. Nevertheless, the nature of LCA studies creates difficulties in terms of comparability due to differences in system boundaries, study location, service life and which parts of the construction are actually included in the analysis.

The LCA case study was primarily designed to test the different methodologies proposed in the decision tree on a real-world scenario. In addition to the aforementioned problems with the dynamic modeling choices in the GWP-bio approach, the LCA itself experienced some data problems. First of all, the building is still under construction at the time of writing. The quantities of building materials obtained from the architectural firm and the project developer were preliminary estimates and may differ from these figures in reality. Similarly, the figure used for the amount of initial carbon storage in the wood product was ambiguous. This was therefore assessed through a sensitivity analysis, which showed that the results were quite sensitive to the method used to calculate the initial carbon storage, particularly in relation to the chosen moisture content of the wood product. However, the default value used in the model was relatively low, so the practical carbon storage for “SAWA” could potentially end up being somewhat higher than the one used in this study. Nevertheless, the final GWP values for the whole building are likely to be higher than the results obtained in this study. This is because, in order not to overcomplicate the purpose of the LCA, only the main load-bearing structure of the “SAWA” building was included in the inventory analysis. This consisted of the Derix wood components, both the CLT walls and floors and the glulam beams and columns, including the concrete and steel used to reinforce the structure.

It is important to note that the results of this study should be interpreted with caution if they are to be replicated in other studies due to several assumptions. First, the ISO standards state that it is only allowed to include carbon sequestration in current PCRs if the wood comes from a “sustainable forest” (ISO, 2017). This is a common assumption in all studies of temporary biogenic carbon storage, and in the case of an unsustainably managed forest or deforestation, the results of dynamic approaches may be invalid (Kwok et al., 2020). The Food and Agriculture Organization of the United Nations, FAO, delved into the state of the world's forests and found that the majority of CLT used in buildings comes from Europe or North America, which are not experiencing deforestation, and in fact, the total forest area is increasing (FAO, 2018). Furthermore, the project developer from the case study mentioned that for every tree removed for the construction of “SAWA”, four trees would be replanted. This promise would actually increase the effect of the GWP-bio index and consequently further reduce the overall environmental impact.

The last aspect where this research has shortcomings concerns the biogenic carbon accounting at the end of the life cycle and beyond, in particular the benefits for reuse, recycling or energy recovery. The GWP-bio index initially focuses on the RSL of the product in the building, where it ignores the possibility of extending the lifetime. For this study, a 100% incineration scenario was assumed, which does not discuss the possibility of potential benefits beyond the system boundaries. Although the decision tree proposes a “normal” EoL allocation for biogenic carbon depending on the chosen pathway, it does not specify how this should be done. A potential impact of the approach on these benefits could occur if the storage period is longer than the RSL of the building, thereby increasing the CF for that specific rotation period. However, the focus of this approach remains on the temporary carbon storage in the building's use phase between uptake and release. Therefore, it is recommended that future research build on the study by Garcia et al. (2020) on EoL allocation differences, how biogenic carbon affects this and how dynamic modeling can provide different results in this aspect.

6. Conclusion

6.1. Answers to research questions

This research explored the differences in the modeling of biogenic carbon in LCA and how this affects Global Warming Potential (GWP) results, starting with an introduction to the topic that highlighted the importance of carbon storage in buildings and how this can have a mitigating effect on atmospheric carbon concentrations. Mass timber plays an important role in this potential climate change mitigation strategy, as it has the potential to temporarily store this carbon in the form of biogenic carbon in buildings. LCA standardization documents do not take this temporary storage into account and maintain a carbon neutral principle, which assumes that carbon follows a "short" cycle that does not have a significant impact on the global climate. By following this principle, biogenic carbon uptake and release are considered equal and therefore static characterization factors are applied to the flows in their impact categories (0/0 or -1/+1).

In contrast, some literature on the subject has described that this static method, based on the principle of carbon neutrality, does not capture the benefits of temporary carbon storage and can lead to misleading results. If the dynamics of the forest are taken into account, the storage could directly contribute to the mitigation of climate change, which makes the correct inclusion of biogenic carbon flows in the LCA essential for a comprehensive assessment of the environmental performance of buildings. Therefore, dynamic approaches that include the timing of emissions and the regrowth of forests have been proposed to account for temporary storage. The GWP-bio approach, in contrast to other approaches, is a simplified method based on the concepts of forest rotation period and material storage period in the anthroposphere. This study has investigated the discrepancies on this issue using a specific research design, each with its own subquestions and resulting findings.

A systematic review of 33 recent and relevant LCA studies of bio-based materials was conducted as the first part of the methodology. It focused specifically on how biogenic carbon is modeled in this type of environmental assessment and how the inclusion of temporal factors affects the final GWP results. The majority of the reviewed studies did not include temporal biogenic carbon flows in their analysis and followed the static methods proposed by the European standards, often using the -1/+1 approach. In addition, a significant number of studies did not specify how they modeled biogenic carbon in their LCA, including some that did not bother to mention the concept in the entire paper. Those LCAs that modeled biogenic carbon in a dynamic way found a different GWP compared to the conventional static method, showing that the high variability in LCA methodologies leads to different results.

These findings paved the way for the next methodological part, which was the construction of the decision tree model. This decision tree was believed to contribute to the harmonization process of accounting for biogenic carbon in LCA by providing a structured approach on how to handle it. The existing literature highlighted the need for consistent accounting methods and the benefits of temporary carbon storage. The high variability in LCA methodologies undermines confidence in studies involving the biobased materials that the decision tree aims to address. Based on three main criteria, the model identifies the key decision points in the management of biogenic carbon for LCA studies and guides the practitioner to make more informed decisions. This tool aims to build consensus in LCA studies of bio-based materials, such as mass timber, where the GWP-bio approach plays an important role.

As the decision tree model is a first step towards a consensus on biogenic carbon accounting, the dominant approach of including forest dynamics should be applied correctly. The GWP-bio index is based on only two variables (rotation and storage period) and therefore contains a risk of greenwashing. In order to combat this, this study commits the current guidelines to include (an indication of) the rotation period in the EPDs (Environmental Product Declarations) of all bio-based materials. Furthermore, the value used for the storage period should be equal to the predicted service life of the building as described in the target and scope definitions. Through these measures, the GWP-bio approach can become a relatively reliable starting point for biogenic carbon accounting practices that is easy to implement in LCA software. While it may not be the most accurate, it provides a solid starting point for the harmonization process.

The GWP-bio approach and the decision tree model were then tested with an LCA case study to compare the GWP results of the different biogenic carbon accounting methods. It was found that the “SAWA” building in Rotterdam had a GWP impact of 107 kg CO_2-eq/m^2 for the static approaches based on the carbon neutrality principle (0/0 and -1/+1). The dynamic approach, which accounts for forest regrowth using the GWP-bio index, produced more favorable GWP results, ranging from 39 to -43 CO_2-eq/m^2. The highest GWP results that included forest dynamics were associated with a storage period of 80 years and a rotation period of 100 years ($D_{80/100}$), while the lowest were associated with a storage period of 100 years and a rotation period of 80 years ($D_{100/80}$). The “SAWA” case thus not only showed a significant difference in results between the static and dynamic method, but also found large variations within the dynamic scenarios, showing the importance of choosing the right CF in the GWP-bio index. The results of the case study confirm the lack of consensus that continues to undermine the reliability of the European standards for LCA studies, while at the same time supporting the decision tree model.

Overall, the way biogenic carbon is treated in the LCA of mass timber buildings has a large impact on both the GWP results and the reliability of the LCA. The decision on which characterization factor to choose for biogenic carbon flows is a common problem among practitioners, which often results in them deciding on their own. Firstly, this leads to a different result of the assessment itself, leading to misleading interpretations and potentially discouraging the use of environmentally friendly building materials. Secondly, the credibility of one of the most useful types of environmental assessment is called into question by the lack of clear guidelines on how to carry out part of the analysis accurately. In short, this issue requires a harmonization process involving building companies, government agencies, LCA tool developers, and standards organizations to come up with a single best methodology for biogenic carbon accounting.

6.2. Recommendations

The main finding of this study, the first approach to a harmonized way of accounting for biogenic carbon in LCA, may not be directly the best approach. Therefore, several recommendations can be made for further research and practice.

The advice for building practitioners is to use the current decision tree model and preferably to assess the biogenic carbon of bio-based materials in a dynamic way for their assessments. Although the ISO and European standards do not currently include this type of modeling in their guidelines, the assumption of carbon neutrality is at least ambiguous and does not accurately reflect the reality of the environmental performance of buildings. When considering forest dynamics, the GWP-bio approach should be applied accurately and fairly, as described in the previous section. Since the current standards use the static approaches, especially the -1/+1 approach, it is logical that many LCA studies do not consider temporal aspects. If a static method is used, it is important to choose carefully between the 0/0 or -1/+1 approach. Including only the product and manufacturing stages can lead to misleading results and further problems with the platform for conducting environmental assessments.

As this paper has shown, much research has been done on the issues of biogenic carbon in LCA studies. Since the main obstacle to the implementation of dynamic modeling seems to be its complexity, future research on this topic should look for ways to implement all relevant aspects without having to perform an overly comprehensive analysis. For this reason, the GWP-bio approach is considered by this research to be a good starting point for the model. The first step for LCA tool developers and other future research is to improve the current decision tree by evaluating different modeling approaches and finding a method that contains less uncertainty and unreliability, while still being easy to apply. A more detailed and focused study of the EoL allocation and Module D benefits regarding biogenic carbon is needed, as well as an extension to more types of bio-based materials such as the rapidly growing straw, hemp and bamboo. These are ongoing processes where the sensitivity of the results needs to be well understood before proposing a tool that correctly assesses all the benefits and negative consequences of biogenic carbon.

The main recommendation for the next steps is to reach a consensus on the issue and to start a harmonization process between different parties regarding the choices made by the research. As J. H. Andersen et al. (2022) mentioned in their study, similar processes have been carried out, which eventually led to the adoption in European standards. All results of different scenario modeling from the most relevant research should be systematically reviewed and discussed among different parties. Governmental bodies have the power and ability to bring these parties together and define the short-term actions to improve LCA discrepancies. While the top researchers in the field bring the necessary proposals to the table, the standardization organizations (ISO, CEN and MPG) are the key players in these discussions. Together with the policy makers, this group will decide on the new updates of the LCA guidelines. It is also essential that representatives of the building sector are involved, as they are the ones who will ultimately have to deal with the consequences of the changes. The building sector in general should focus on the growing interest in building with bio-based materials, where the temporary benefits of carbon storage are an important factor.

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8. Appendices

8.1. Appendix A: Excel file 'Sys_review'

The Excel file containing additional information on the studies included in the systematic review. The first sheet shows all the studies that were initially considered before the various screening processes. The second sheet contains the final sample size, including general information about the paper such as location, area, and system boundaries. The third sheet is the most important for this paper as it contains the biogenic carbon modeling characteristics. In addition to providing the GWP results of the study, this sheet also provides the approach used to model biogenic carbon and the modules used to account for uptake, release, and potential storage.

8.2. Appendix B: Excel file 'LCA_inventory'

The Excel file containing supplementary information on the "SAWA" LCA case study. The first and second sheets cover the inputs for the Activity Browser software, including material quantities and transport distances. The third sheet gives a complete overview of the exact flows from the standard LCA model. The fourth sheet shows the output of the Activity Browser results, while the fifth sheet shows the results of the biogenic carbon modeling processes. Finally, the sensitivity analysis can be found on the last sheet of the file.