Temporal Complexity, how time influences life cycle assessments of bio-based materials

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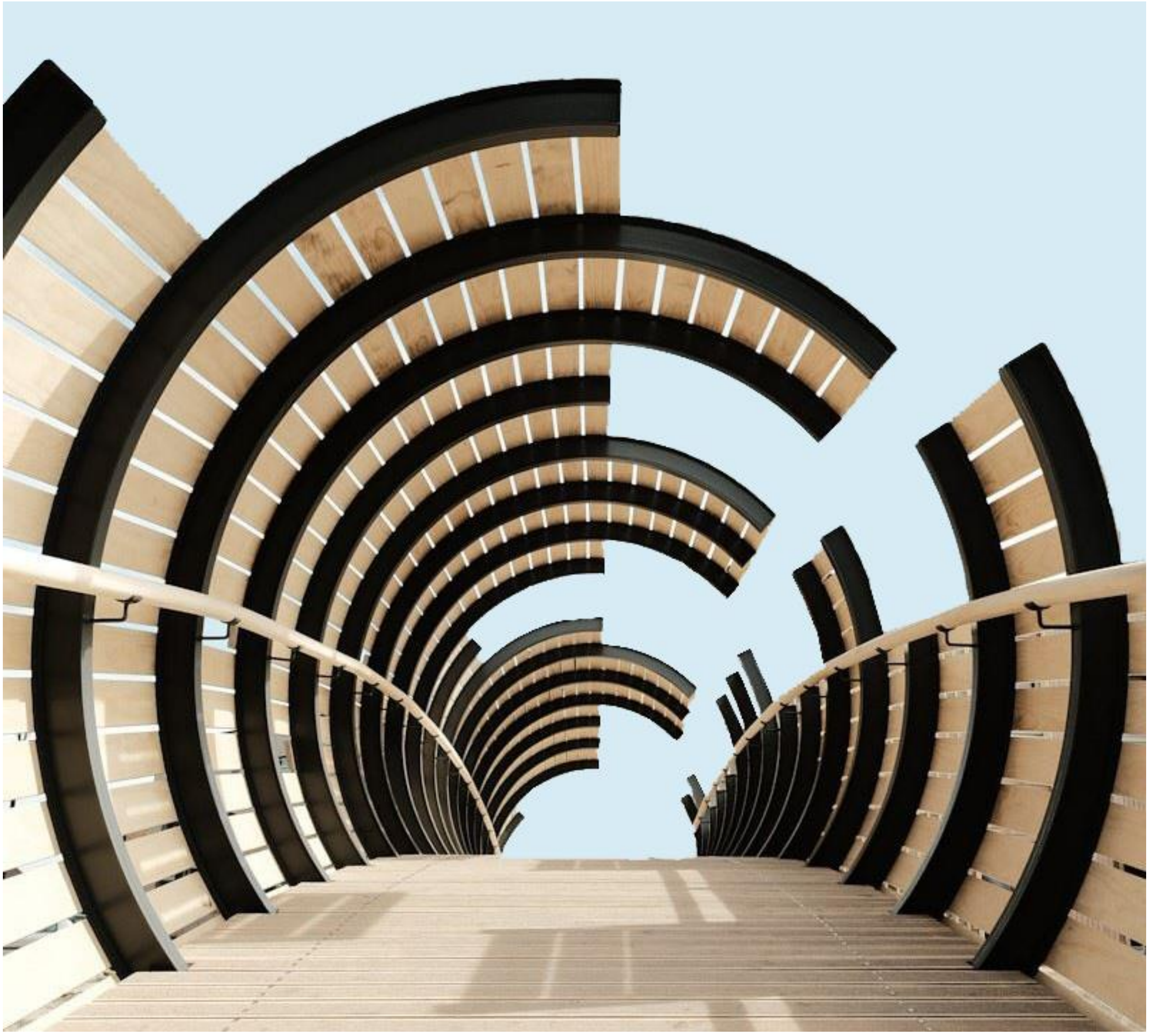

Thesis by: Stijn van den Berg

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A research on the temporal aspects of life cycle assessments.

Author: Stijn van den Berg

Student number Delft University of Technology: 5669472

Student number Wageningen University of Research: 1142267

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Supervisors:

Dr. A. Meijer | Delft University of Technology | Architecture and the Built Environment | Architectural Engineering and Technology

Ing. P. de Jong | Delft University of Technology | Architecture and the Built Environment | Management in the Built Environment

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Abstract

Environmental harm is an influencing factor in policymaking, as climate pressures are frequently on the global agenda. An important tool to guide decision-making in the construction industry is the life cycle assessment (LCA) methodology, where the quantification of environmental harm is realised. In the method, an estimation of numerous environmental impact indicators can be made by assessing the various life cycles of a product, material, or process. Bio-based materials have been considered a valuable option to mitigate climate change. However, the LCA methodology appears to disregard certain characteristics of the material that could potentially improve their corresponding results. With the growth of bio-based materials, atmospheric carbon is stored as biogenic carbon and subsequently released at the end-of-life, the last life cycle phase of a material. The current methodology is unable to credit such storage, as it models all emissions through the life cycle as if they occurred at the same time. This research aims to explore the various options to comprehend, assess, and credit the storage of biogenic carbon. First, the different approaches to assess the storage of biogenic carbon, that are described in the literature, are assessed. Second, various methods to credit the timing of emissions in the LCA methodology will be elaborated upon. Third, the different currently active European standards are described. For biogenic carbon assessment, three methods were described: the 0/0 method, the -1/1 method, and the dynamic method. Here it was concluded that, respectively, complexity and accuracy increased, making practical implementation difficult but potentially valuable. Especially, the dynamic approach is shown to be a promising tool to accurately assess temporalities within the life cycle of a product. For possible crediting mechanisms, three methods were discussed: the Moura-Costa, Lashof, and ILCD crediting methods. Each method was based on specific assumptions, which resulted in varying credit strengths. In general, each crediting mechanism answered the demand for crediting delayed emissions, but to decide whether one of the methods is better suited than the other, further research is necessary. It is found that the organisational complexity of standardisation within the European Union influences possible alterations in the LCA. However, the research can conclude that the methodology is currently unable to capture the benefits of biogenic carbon storage, and by looking into potential crediting mechanisms, this limitation can be answered. Depending on the demand of our climate and, therefore, of policymakers, possible crediting mechanisms for the storage of biogenic carbon can be considered to be implemented through the LCA methodology.

Keywords: life cycle assessment (LCA), biogenic carbon, carbon crediting, bio-based materials

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1 List of Abbreviations

Abbreviation	Definition
CE	Circular Economy
EC	European Commission
EN	European Norm
EoL	End-of-Life
EPD	Environmental Product Declarations
EU	European Union
GHG	Greenhouse gasses
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
Luluc	Land use and land use change
PCR	Product Category Rules

2 Introduction

Generally, it is acknowledged that there exists a significant driver for a more sustainable future. Next to the concerns for quick climate change, the availability of energy and materials is envisioned to only decrease. The European Union (EU) aims in the future to transition to a circular economy (CE) where material loops are closed, waste is reduced, and resource efficiency is enhanced (EC, 2015). The CE aims to maximise material usage and the utilisation of available resources in a product. Transitioning towards a CE can support minimising pollution, emissions, and waste in the built environment (Van Stijn et al., 2022). In general, the CE can be identified as a regenerative system where new resource input, waste, emissions, and energy leakage are minimised by slowing and closing material and energy loops (Geissdoerfer et al., 2017).

However, the current economic system is far from circular (Haas et al., 2015). Presently, the economic system is based on continuous growth and has limited room for sustaining its levels and boundaries. Kate Raworth (2017) argued for a different system, a system where growth is not the goal but sustaining society within the boundaries of our system. In Figure 1, this system is shown, the Doughnut Economy. The Doughnut Economy is a system where two boundaries are present: one that portrays our ecological ceiling and another that is our social foundation. Being located within these two boundaries presents a safe and just space for humanity. Having society outside these boundaries either means that society is surpassing the ecological boundary or our social foundation. Currently, our society is not located within these boundaries, where certain countries score outside the ecological ceiling and others have a shortfall in the social foundation. The Doughnut Economy sets the ambition, but the development of such a system is ongoing and might not even be reached in the future.

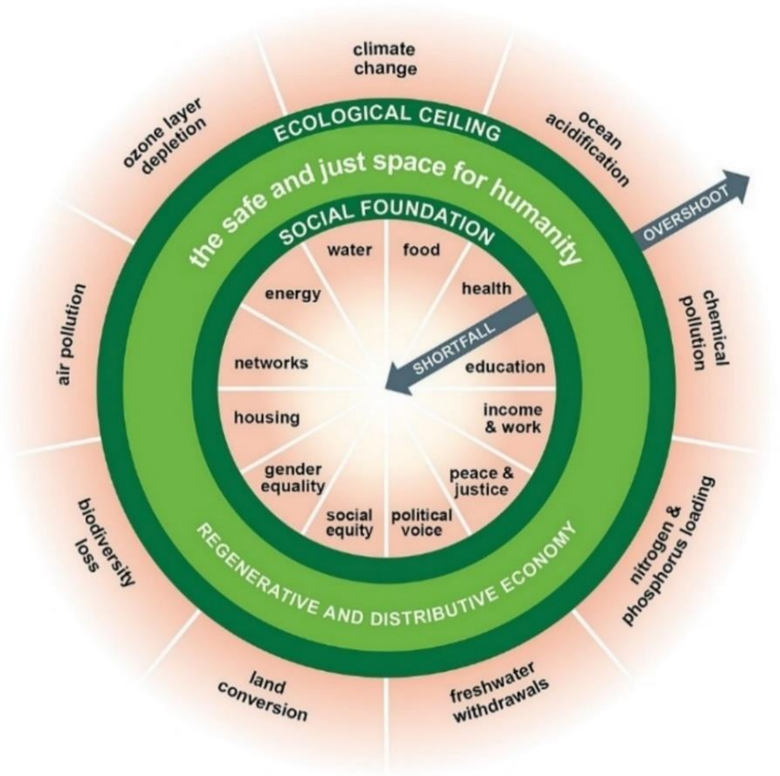


Figure 1 Representation of the doughnut economy by Kate Raworth (2017).

According to Ness and Xing (2017) and Bahramian and Yetilmezsoy (2000), the building industry currently contributes significantly to the present environmental changes by consuming 40% of the world's resources and emitting close to 30% of its share of greenhouse gases (GHGs). Due to the sector's nature to consume materials, the implementation of a CE is a significant challenge, but the potential for impact is at least equally compelling. Unfortunately, the development towards such a system appears to be difficult and complex, resulting in a relatively slow transition (Hartley et al., 2020). Potentially, the way society considers the industry within our economic system causes this difficulty, as the sector is once again aimed at continuous growth and investment thinking (Raworth, 2017). Instead, the idea of a Doughnut Economy could potentially provide the tools to guide our society toward a CE. Both systems, the circular economy and Doughnut Economy, complement each other and could be used as the basis on which governments and larger-scale instances could base their laws and regulations. To guide our society towards a preferred economy, influential changes have to be realised in the current system via intergovernmental organisations, such as the EU and the UN. Considering the objective of CE and the excessive use of materials, the construction sector is an important sector that has to be altered accordingly via these organisations. Nonetheless, the standards created by the EU or other instances are commonly made to look back instead of forward. As these standards are prescriptive, they can hamper innovation instead of promoting it (Pelkmans & Renda, 2014).

A material with a strong contribution to the environmental harm of the sector is cement, which is responsible for 5% of global carbon dioxide emissions (Worrell et al., 2001). Manufacturing, transport, and end-of-life processing are all contributing to a harmful construction material with higher levels of GHG emissions and therefore strengthening climate change (Wu et al., 2014). Just like cement, construction materials such as metals and glass can be identified as mineral-based, often characterised by extraction from finite resources and being energy intensive (Berge, 2009). Timber, a sustainable material, has become a competitive alternative to concrete in light of the EU's stated goals and industry challenges. This material has been extensively utilised in the past and possesses regenerative properties, is bio-based, and is easy to process (Ramage et al., 2017). It is commonly believed that timber-based construction has the potential to mitigate the adverse effects of the construction industry (Skullestad et al., 2016). Still, there exist obstacles that counteract large-scale implementation, such as costs, building regulations, and an imbalance in supply and demand. However, due to the various climate goals, increased awareness of the potential role of mitigating climate change by sequestering and storing atmospheric carbon in construction materials can be noticed (Arehart et al., 2021; Guest & Strømman, 2014; Hawkins et al., 2021). With the growth of bio-based materials, atmospheric carbon is stored via photosynthesis, creating an opposite transfer of carbon compared to emissions (Brandão et al., 2013). Bio-based products can contain around half of their dry weight in carbon and therefore have a significant sinking effect (Pittau et al., 2018). This applies not only to timber but also to products like hemp and straw, which require far shorter rotation times to store carbon. Because of that, materials with such short rotation times can be very effective in the storage of atmospheric carbon (Pittau et al., 2019).

The comparability of sustainable practices and materials is a complex phenomenon that is dependent on a wide variety of factors. Each material has specific requirements that make it sustainable or not. Commonly, GHG emissions are taken as a driving force for sustainable comparisons, but factors such as acidification, eutrophication potential, and many more can give different results throughout these analyses (Morris et al., 2021). A comprehensive assessment of the different impacts and trade-offs between environmental pressures is necessary for policymakers to transition our society toward a sustainable one (Sala et al., 2021). To aid in this need, life cycle assessment (LCA) was introduced globally. The most profound organisation for standardising this assessment is the International Organization for Standardization (ISO). The ISO 14040 standard (2006a) described LCA as a compilation and evaluation of inputs, outputs, and potential environmental impacts of a product throughout the entirety of its life cycle. As described by Sala et al. (2021), the method gives the possibility of comparing quantitative information on the environmental performance of goods and services. This makes it a valuable tool for policymakers to implement sustainability in their policies. There still exist obstacles that counteract the intended use of LCAs, such as variations in scope, definition, functional unit, and data validity, but the method is increasingly represented in policies throughout the EU (Bahramian & Yetilmezsoy, 2020). Nonetheless, the method represents itself as a viable way to estimate the environmental harm of a product, service, or material. In Figure 1, where the Doughnut economy is shown, it is observed that an ecological ceiling is present. The LCA methodology is potentially a method to quantify this ceiling and to create a functional way of comparison in this domain. On the contrary, the social foundation can also be exceeded. Currently, the methodology is unable to capture components such as inequity, child labour, and other social injustices. Potentially, in the future, the LCA methodology can be applied to all components of the Doughnut economy. However, in this research, the approach will be aimed at environmental quantification.

When considering timber-based or, in general, bio-based materials, it would be expected that a better LCA score is generated compared to traditional construction materials. This is due to its capability to capture carbon and by being regenerative (Ramage et al., 2017). Yet in certain scenarios, the LCA shows unexpected counterintuitive results, with smaller differences between the materials or even better scores for traditional construction materials (Morris et al., 2021). The research of Morris et al. (2021) mentions three important factors that can negatively influence the results of timber using LCA as the quantification method, of which one is more a practical implementation and two are methodological assumptions. In this research, the general assumptions of the various materials that were compared stayed the same (e.g., transportation, equipment), as it was particularly focused on the methodological choices in the LCA.

The first is the translation of the end-of-life (EoL) phase in the assessment tool. The EoL phase for construction materials is the period where environmental impact is calculated for deconstruction, transport, waste processing, and disposal. In a practical comparison, traditional materials tend to score better as the infrastructure for such materials is further developed. However, in the research of Morris et al. (2021) a controlled comparison took place where these practicalities are equalised. Nonetheless, for the EoL phase of timber, there are three commonly used scenarios: incineration, landfill disposal, and recycling. The most profound method of wood disposal is incineration, where bio-energy generation is its main benefit (Hafner et al., 2014). On the contrary, it is mentioned that the material has a high potential to be reused, rather than deciding for downcycling or energy generation (Ramage et al., 2017). The second important assumption described by Morris et al. (2021), is the treatment of biogenic carbon. While executing LCAs for timber-based construction, the assumption of carbon neutrality is widely adopted. It presumes that the CO_2 absorbed during photosynthesis is equal to the CO_2 emitted during the EoL, therefore neglecting any effects of carbon storage. One of the benefits of timber in construction is that it can store carbon, which counteracts the accumulation of greenhouse gases in our atmosphere (Skullestad et al., 2016). Due to the assumption of carbon neutrality, this benefit is not credited in the LCA methodology. The last assumption concerns the timing of emissions, as the time delay created by biogenic storage can reduce atmospheric CO_2 levels. Such timing can be preferable to no consideration of temporalities, but in the LCA methodology, no crediting of this temporality is present. Currently, LCAs are an aggregation of all the different life cycle phases of a product, while actually each phase happens separately with different harm to the environment at different times. On the other hand, for timber, it could be very beneficial to add such detail to an LCA as it stores carbon while regenerating new material.

Nonetheless, no clear consensus on how the timing of emissions should be managed has been found (Levasseur et al., 2012).

An LCA consists of various impact categories that quantify specific aspects of environmental harm. In the context of biogenic carbon and emission timing, one specific impact category is distinguished, the global warming potential (GWP). This impact category aggregates various GHGs into a CO_2 equivalent and uses that to compare the potential of global warming (Solomon et al., 2007). All emissions during the lifetime of a product are combined into a single number. In Equation (1), the general calculation for the GWP of a single pulse emission and GHG is presented. For the calculation of the entire GWP of a product, multiple pulse emissions are modelled, and various GHGs are calculated per pulse emission.

$$GWP = \frac{C_0 \int_0^{TH} \alpha_{GHG} * \gamma_{GHG}(t)dt}{\int_0^{TH} \alpha_{CO2} * \gamma_{CO2}(t)dt}$$

(1)

In Equation (1), the numerator portrays the pulse emission of a specific GHG, and the denominator normalises this value towards the CO_2 equivalent. The magnitude of the pulse emission is assigned to C_0, and the radiative efficiency of a GHG is illustrated by α_{GHG}. For CO_2, the radiative efficiency is commonly used as a constant with a value of 1.4E-5 watts per square meter per part per billion ($W/m^2/ppb$) (Guest et al., 2013). For other GHGs, different radiative efficiencies are used depending on the concentration in the atmosphere. Additionally, γ_{CO2} denotes the decay of CO_2. This decay is possible for any GHG that is considered during a pulse emission. Any difference in greenhouse gases is represented by the notation GHG in subscript, which enables the GWP to be calculated based on the unique decay function of each gas. For the decay of carbon dioxide, the Bern Model is commonly used (Houghton et al., 1995), while for other GHGs, different decay functions are applied. The Bern Model is shown in Equation (*2*) and elaborated upon in Chapter 4.2. Finally, the integral is used to calculate the surface area underneath the decay function for the entire time horizon and to create the final GWP.

The calculation of the GWP can be considered relatively simple and transparent, yet is often the target of criticism (Almeida et al., 2015). During the aggregation, all emissions that occur during the lifetime of a product are modelled as if they occurred at time 0, while in reality, they can occur an entire generation later. In combination with the characteristics of bio-based construction materials, a potential level of detail is absent. The following research is aimed at enhancing the methodology's capability to capture environmental harm by getting a better understanding of the characteristics of bio-based construction materials. This increased understanding is established by looking at the considerations of biogenic carbon, the crediting of emission timing, and the current standards within the EU.

3 Methodology

With climate change on the agenda, the quantification of environmental harm is a contributing factor in policy-making throughout Europe (Röck et al., 2021; Di Maria et al., 2018). The most widely accepted method to quantify this environmental harm is life cycle assessment (LCA). Here, the entire life cycle of a product or building is evaluated, resulting in a single aggregated value for the LCA. During this estimation, certain assumptions or considerations are made that influence the final result of the LCA, changing the final comparison and therefore future policy making. Considering bio-based materials, the consideration of biogenic carbon can influence the results of the LCA. Additionally, the crediting of carbon storage or the delay of emissions can be an important factor that would change the comparison of materials throughout the methodology. To improve or prepare future policy-making, this research will answer the question: **How does the treatment of biogenic carbon and the crediting of emission timing influence the results of life cycle assessments considering bio-based materials?**

To answer this, four sub-questions were formulated that contribute to answering the main research question.

i. What are the current approaches for biogenic carbon in LCAs, and how do they compare themselves with each other?
ii. What methods exist to credit the timing of emissions, and what assumptions are made that differentiate them from each other?
iii. How do European standards address biogenic carbon and emission timing?
iv. How are the approaches to biogenic carbon and the methods of crediting the timing of emissions related to each other and the current European standards?

The data collected and used for this research will be gathered from academic sources and literature. Additionally, information originating from the European Commission and ISO standards will be used to conceptualise the current field in which LCAs are conducted. For the analysis, a literature review will be conducted following an integrative approach, as formulated by Snyder (2019). According to Snyder (2019), this approach is often intended to either address mature topics or relatively new and emerging topics. The LCA methodology can be regarded as a mature concept because it has received a lot of research and has been applied in practice. On the other hand, the approach to biogenic carbon and the timing of emissions can be considered emerging due to the lack of consensus within the academic field. The goal of this literature review aligns with that of Snyder (2019), who state that an integrative review can be aimed at creating an overview of the knowledge base, critically reviewing it, and potentially re-conceptualise it. Similarly, this study aims to give an overview of the various means to manage biogenic carbon and its corresponding temporalities. By doing this, the study will be able to combine and then review the numerous approaches and strategies that have been documented in the literature. For the analysis, no specific standards or framework are connected to the integrative approach, but it is commonly used to critically analyse the main ideas and relationships of the topic (Whittemore & Knafl, 2005).

By using an integrative approach to critically analyse current literature, the following research design is created, as shown in Figure 2. Throughout the research, the results of the LCAs will be specified in the GWP, as the influence of biogenic carbon is mainly observed in that specific impact category. Five chapters are shown in the picture, each of which begins with the matching chapter number from the report. Two sorts of relevance, scientific relevance and practical relevance, are offered as the foundation for the research design. The chapters can connect to a single relevance or a mixture of them. The research design starts with the problem statement described in the introduction (Chapter 2). Subsequently, three separate individual chapters arise from the problem statement. These chapters correspond with the first three sub-questions of the study. First, the biogenic carbon approaches, where sub-question (i.) will be answered. Second, the crediting methods for emission timing with sub-question (ii.), and third, the current European standards answering question (iii.). For the creation of graphs, the software Microsoft Excel (Microsoft Corporation, 2012) will be used. Subsequently, the three individually assessed components will be combined in the discussion, where the three components and corresponding research questions are first combined. By combining the various components, new insights can be created and relationships be found. These can be used to answer sub-question (iv.). Additionally, in the discussion chapter, all findings will be used to relate to the problem statement. Here, the various results will be used to reflect on the findings and other components of the problem statement. The final sub-chapter of the discussion will reflect on the limitations of the methodology and the results found. The study will be finalised in the conclusion chapter, concluding the main findings and making recommendations for future research.

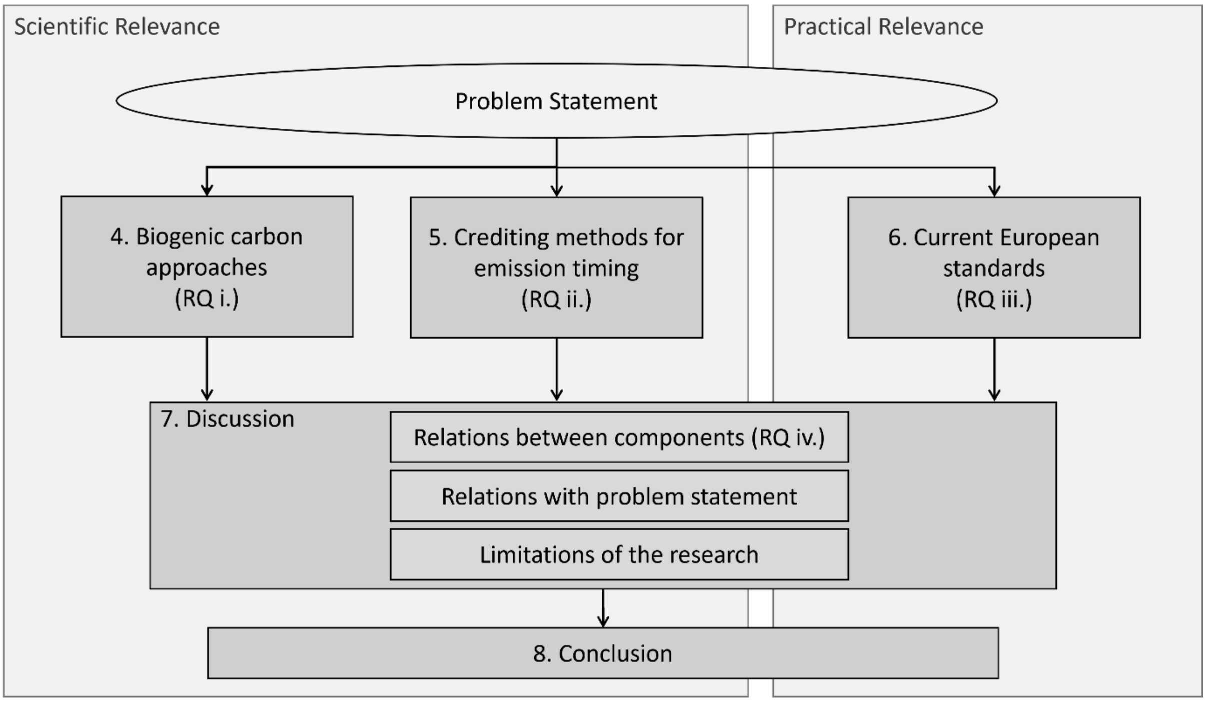


Figure 2 Research design containing the five chapters of the research and the answered research questions (RQs).

Biogenic carbon approaches (Chapter 4)

In this chapter, three existing methods of biogenic carbon storage in LCAs will be discussed based on the study by Hoxha et al. (2020). By applying an integrative literature review, sub-question (i.) will be answered. First, the static approaches, which contain two of the three methods, will be described and elaborated upon. Second, the dynamic approach (Levasseur et al., 2010) towards biogenic carbon storage within LCAs will be defined and illustrated. Third, the two approaches are considered in a comparative sub-chapter, where the assumptions, benefits, and limitations of each method are discussed.

Crediting methods for emission timing (Chapter 5)

To account for the benefit of storing biogenic carbon, crediting mechanisms for the timing of emissions have been emerging in the literature. In this chapter, three scientifically-based crediting mechanisms related to the LCA methodology will be presented. The article written by Brandão et al. (2013) functions as a guideline for the chapter, as it briefly elaborates on various scientific crediting mechanisms. Each crediting method will be evaluated separately, with the assumptions, equations, and relative results shown in comparison to the traditional method. Subsequently, the three crediting methods will be combined in a comparison between the current traditional LCA method and each other. By doing so, an answer can be formulated for sub-question (ii).

Current European standards (Chapter 6)

This chapter accounts for the present applied standards throughout Europe regarding LCAs. Here, the European standards EN 15978 (CEN, 2012) and EN 15804 + A2 (CEN, 2019) will be mainly elaborated upon. Starting with the context in which LCAs are conducted within the EU and its standards, followed by an in-depth analysis of the two standards. During this, the analysis will be mainly focussed on the consideration of biogenic carbon and the perception of time and its crediting. This will answer sub-question (iii.)

Discussion (Chapter 7)

In this chapter, the findings of the research will be combined, related to the problem statement, and reflected upon. First, the various findings will be combined and used to assess the relationships between the previous chapters. Here, sub-question (iv.) will be answered. Second, the findings are related to the initial problem statement. By doing so, new insights into the complexity of applying LCAs and their temporality can be gained. Third, the limitations of the research will be reflected upon. This can lead to ways to further improve the research or recommendations for new directions in the context of the problem.

Conclusion (Chapter 8)

The final chapter of the research will contain a short description of the problem statement, the key findings, and the main takeaways. Lastly, the recommendations of the study are summarised and presented for future research.

4 Biogenic Carbon Approaches

In the following chapter, two approaches to biogenic carbon storage, containing three methods, will be assessed. The first two methods are considered static due to their relatively simple regard for the temporalities of the life cycle. Subsequently, a dynamic approach will be discussed that assesses temporality in more detail. At last, the various approaches and methods are compared based on their assumptions, benefits, and limitations.

4.1 Static Approaches

Two methods for biogenic carbon storage are commonly referred to as static, meaning that their consideration of time is considered relatively simple (Almeida et al., 2015). The first method is the 0/0 method, which is frequently used in practice and commonly referred to as the carbon-neutral method (Morris et al., 2021). It assumes that the CO_2 stored in a bio-based product is equally balanced with its CO_2 emissions at the end of its life. It is therefore possible to disregard any biogenic carbon, as the uptake and release of carbon are equal. Figure 3 shows an adjusted version of the figure shown in the article by Hoxha et al. (2020), where a schematic situation of a bio-based product is visualised. In this figure, a distinction is made between three phases of the product: the growing phase, the building phase, and the recycling phase. Part of the building and recycling phase is subdivided into the stages presented by European Standard EN-15978 (CEN, 2012), with module A as the construction process stage, module B as the use stage, module C as the end-of-life stage, and module D where the benefits and drawbacks beyond the system boundaries can be shown. In Chapter 6, the European Standards and their role in biogenic carbon will be further elaborated upon. Additionally, in Figure 3, it is seen that during the various phases of the life cycle, only fossil emissions of greenhouse gasses (GHGs) take place, represented by a black arrow and text. With the absence of a green arrow and text, it means that no input or output of biogenic carbon is considered.

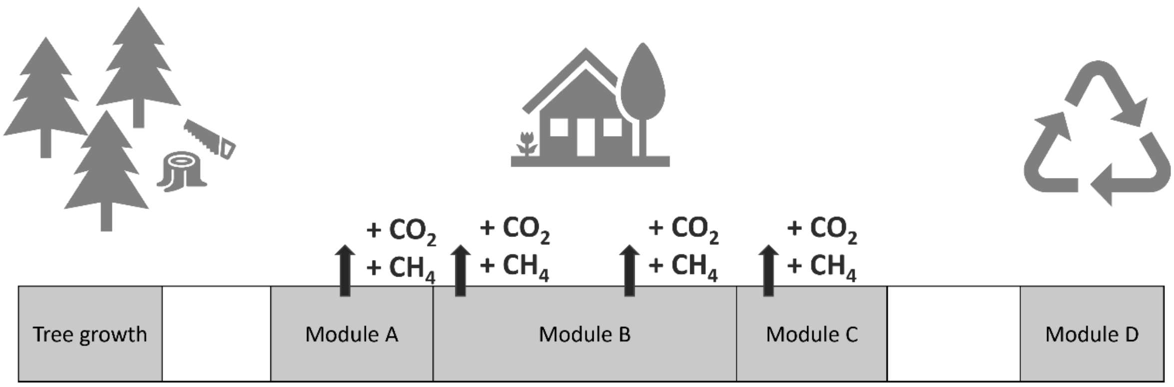


Figure 3 Schematic illustration of the 0/0 method through the life cycle phases. In black the output of fossil-based emissions is presented.

The second method similarly assumes that the sequestration is equal to the emissions of bio-based products. But instead of giving biogenic carbon flows an impact score of 0, all flows of biogenic carbon are considered. Most importantly, state the intake of CO_2 (-1) and, in a later stage, output of CO_2 (+1). In Figure 4, this is schematically presented. The sequestered carbon during the growth of the product is shown as a negative emission in module A. In module C, a fraction of the emissions are emitted, and another fraction is potentially transferred to module D, where a new product can be created. In the figure, the green arrows and text represent the biogenic carbon input and output, and in black, the fossil-based emissions. Across all the different modules, the net biogenic CO_2 will result in zero as the input of biogenic carbon in module A is equal to the output in module C. Different from the 0/0 method, an overview is created with all the carbon flows in the system.

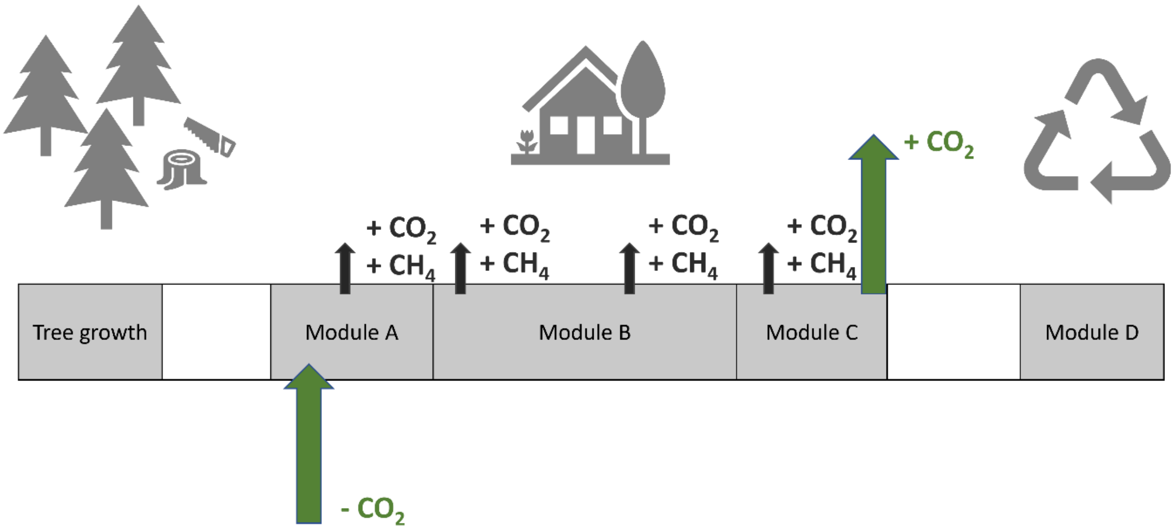


Figure 4 Schematic illustration of the -1/1 method through the life cycle phases. In black the fossil-based emissions are presented and in green the input and output of biogenic carbon.

Both methods result in an equal accumulated GWP, although their development through the modules is different. In Figure 5, a hypothetical life cycle of a product shows how the accumulated GWP changes, based on the 0/0 and -1/1 methods. With the -1/1 method, a decrease can be observed in the GWP in phase A1. Subsequently, it is seen that the two methods follow a parallel growth pattern, but with a stronger increase during module C for the -1/1 method. Due to an equal release of biogenic carbon in the end-of-life phase as the storage in phase A1, both result in the same accumulated value at the end of their life cycles.

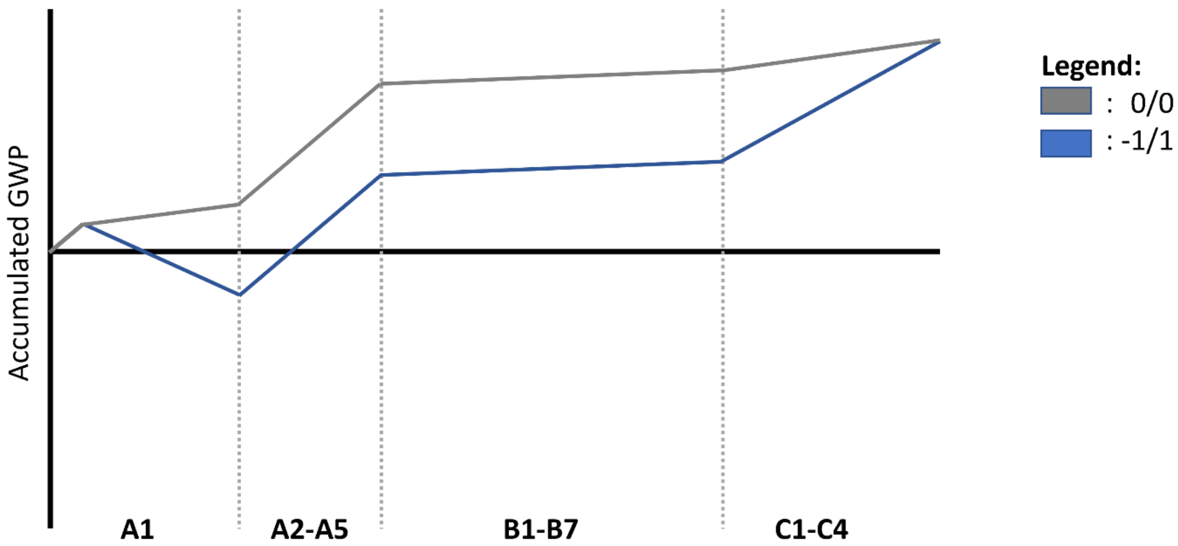


Figure 5 Hypothetical accumulated GWP of the 0/0 and -1/1 method over the life cycles.

4.2 Dynamic Approach

The previous methods could be considered static as no consideration of temporal processes such as emission timing, biomass growth, and rotation periods was taken. With bio-based materials, this temporality is a potential influencing component of the LCA, as the growth of the product influences its efficiency in capturing biogenic carbon (Pittau et al., 2018). A solution to capture this temporality is to implement a more dynamic approach. Environmental harm is a temporal process (Pahl et al., 2014), for example, releasing a large number of pollutants instantaneously will not have an equally harmful effect on the environment as the same amount distributed over a longer period (Levasseur et al., 2013). Because of this, Levasseur et al. (2010) introduced the concept of a dynamic LCA to improve the methodology in its capability to capture temporal effects through a product's lifetime. Different from traditional methodologies, the method of Levasseur et al. (2010) uses the temporal profiles of emissions so that each emission can be considered as a function of time rather than a single number.

An example of such a function of time is the Bern Model (Houghton et al., 1995). Regarding atmospheric carbon, it is important to assess its residence time in the atmosphere because the natural sequestering of carbon lowers its concentration in the atmosphere. The Bern Model is considered a powerful and accurate model to estimate the residence time of CO_2. The model shows how a pulse emission of CO_2 develops and decreases over time. Through research, the model resulted in the following more accurate revised equation presented by Fearnside et al. (2000):

$$C_t = a_0 + \sum_{i=1}^{4} a_i * e^{-t/\tau_i} \tag{2}$$

a_0 = 0.175602, a_1 = 0.137467, $a_2 = 0.185762$, $a_3 = 0.242302$, $a_4 = 0.258868$

τ_1 = 421.093, τ_2 = 70.5965, τ_3 = 21.42165, τ_4 = 3.41537

In Figure 6, using the Bern Model, the development of a pulse emission of a tonne of CO_2 for 100 years is shown using Equation (*2*). On the y-axis, the amount of atmospheric CO_2 in tonnes is shown, and on the x-axis, the number of years after the pulse emission. It is seen that atmospheric CO_2 decreases quicker in the earlier years than in the years further from the pulse emission. After 100 years, approximately 33% of the original emission is still present in the atmosphere, meaning that 67% was sequestered by natural processes during that time. With a time horizon longer than 100 years, the concentration of CO_2 would further decrease as sequestration of carbon would still take place.

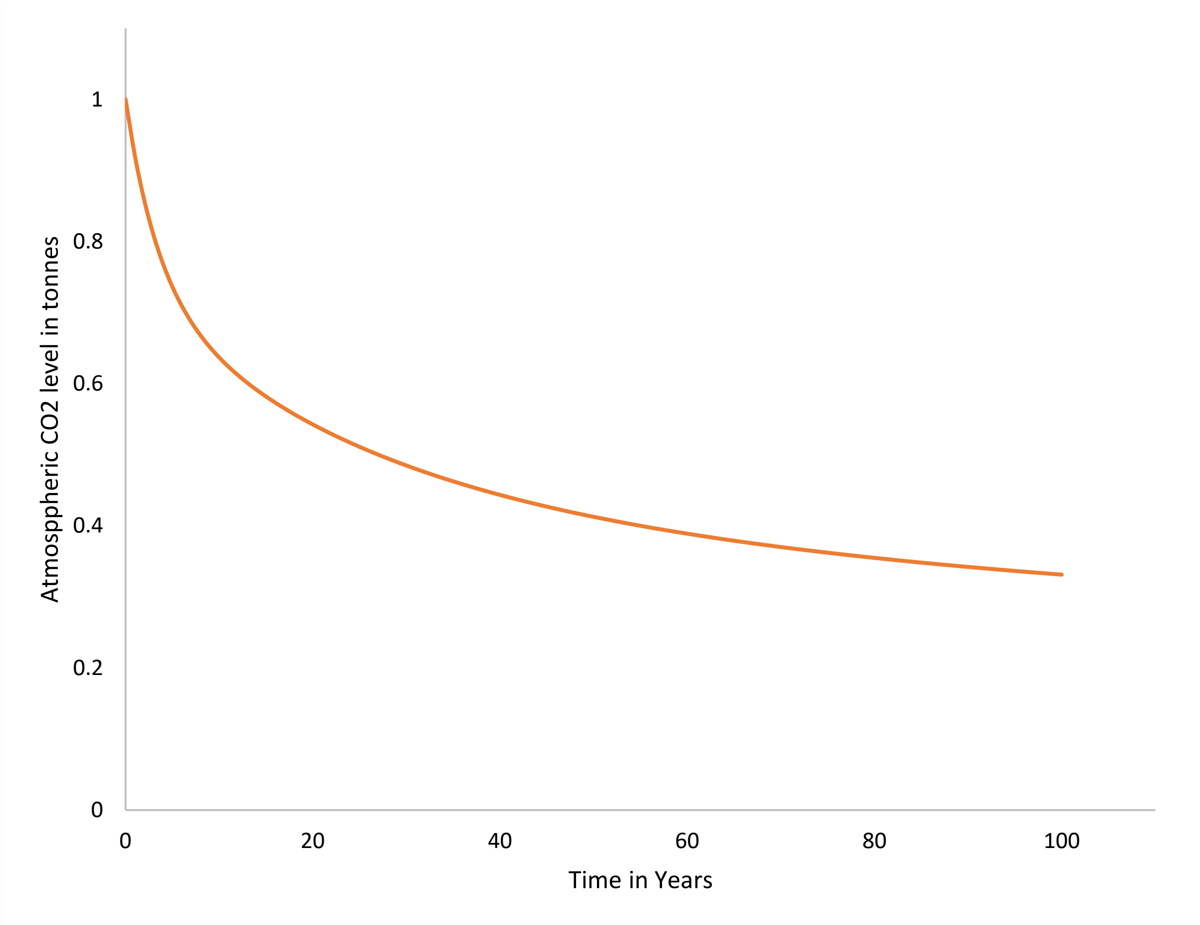


Figure 6 Illustration of the sequestering of atmospheric carbon of a single tonne pulse emission using the Bern Model.

Both for a static approach and a dynamic one, the Bern Model is used to model the atmospheric concentrations of a pulse emission over the TH. For the static approach, all emissions are considered to occur at time 0. By using the Bern Model, the decay of all pulse emissions is modelled over the entire time horizon. Even though an emission took place in the final years of the lifetime, the Bern Model is used for the entirety of the life cycle. This is a deviation from reality, and therefore a missed opportunity in the methodology (Almeida et al., 2015). When the dynamic approach is considered by Levasseur et al. (2010), each year within the time horizon of a product is considered individually. This means that if a pulse emission occurs at year 60, the Bern Model is applied for 40 years instead of 100 years. Subsequently, all emissions of a product are assessed separately, corresponding with their year of occurrence, and then aggregated into one number describing the global warming potential (GWP) of the product. By doing so, the dynamic approach created a benefit for delayed pulse emissions as the moment of occurrence influences the surface area under the model. If the emission takes place at a later stage of its lifetime, the width of the graph decreases, and with that, the surface area as well. In Equation (3), the dynamic approach is presented. Different from Equation (1), where a calculation takes place for a single pulse emission at t = 0, the dynamic approach assesses each year separately and calculates the surface area from that time (t_j) until the TH. Represented by C_{t_j}, the severity of the pulse emission is considered for each year. For the calculation of the entire GWP, each GHG should be considered individually, creating another summation for the various GHGs.

$$GWP_{dynamic} = \sum_{t_j}^{TH} \frac{C_{t_j} \int_{t_j}^{TH} \alpha_{GHG} * \gamma_{GHG}(t_j)dt}{\int_{t_j}^{TH} \alpha_{CO2} * \gamma_{CO2}(t_j)dt}$$

(3)

As each year can be assessed separately, it becomes possible to create a crediting mechanism closely related to the temporal characteristics of a product. For example, when considering bio-based materials, the rotation time of crops could influence the results of an LCA (Pittau et al., 2018). Levasseur et al. (2010) mention two scenarios for how sequestration during growth can be modelled in a dynamic LCA. The first option is to sequester CO_2 before the construction of the material, as shown in Figure 7. In the figure, in black, the fossil-based emissions are shown, and in green, the benefit of biogenic carbon is presented. The graph shows on the x-axis time and on the y-axis the amount of biogenic carbon, meaning that the longer the consideration of biomass growth, the higher the benefit of biogenic carbon. In this example, the trees or any other bio-based product grow before the construction, resulting in an immediate benefit for the sequestered carbon in the life cycle. Different from the -1/1 method, the stored biogenic carbon is used for a negative emission, and the release is not necessarily the same amount as the storage. The second option is considering CO_2 sequestration during the lifetime of a product, which is presented in Figure 8. In this example, the graph is located underneath the life phases, meaning that the further in the life cycle, the higher the benefit, as the material had a longer time to grow. As each year is modelled separately, the amount of sequestered carbon increases, resulting in a slowly decreasing environmental harm. Depending on the time of crop rotation, the benefit can increase or decrease during the lifetime of the product. Each option needs to be considered, and if the dynamic approach is conducted widely, consensus needs to be found on which option is best suited. Without this consensus, and if both options are implemented independently, the risk of double crediting is present and therefore contradicts reality (Levasseur et al., 2010).

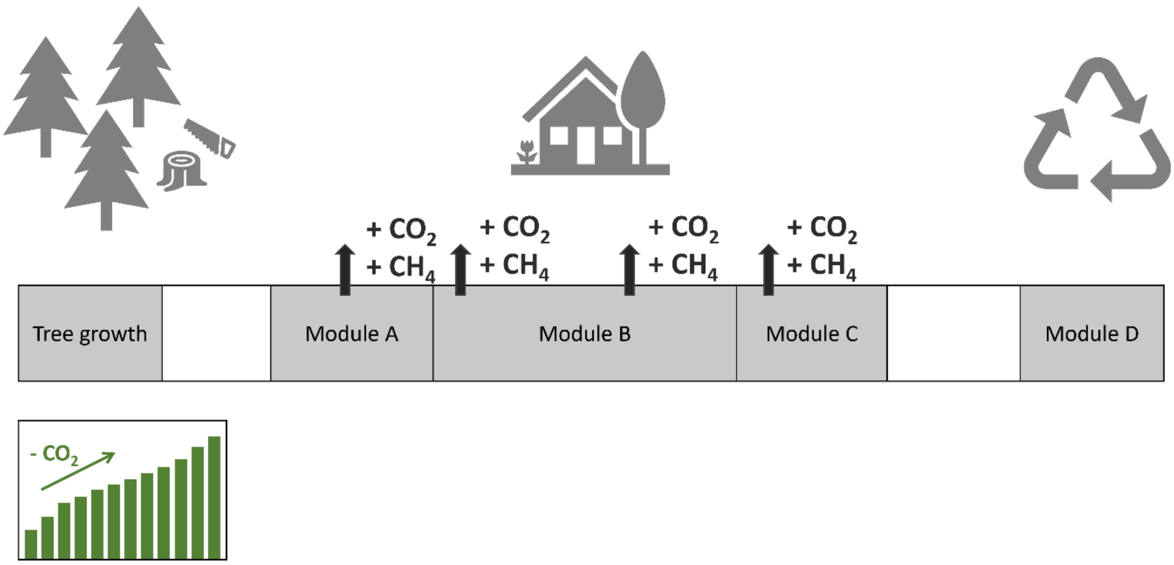


Figure 7 Schematic illustration of a dynamic approach through the life phases. In black fossil-based emissions are presented and in green, a hypothetical development of growing biomass before the life phases is shown as a bio-based credit.

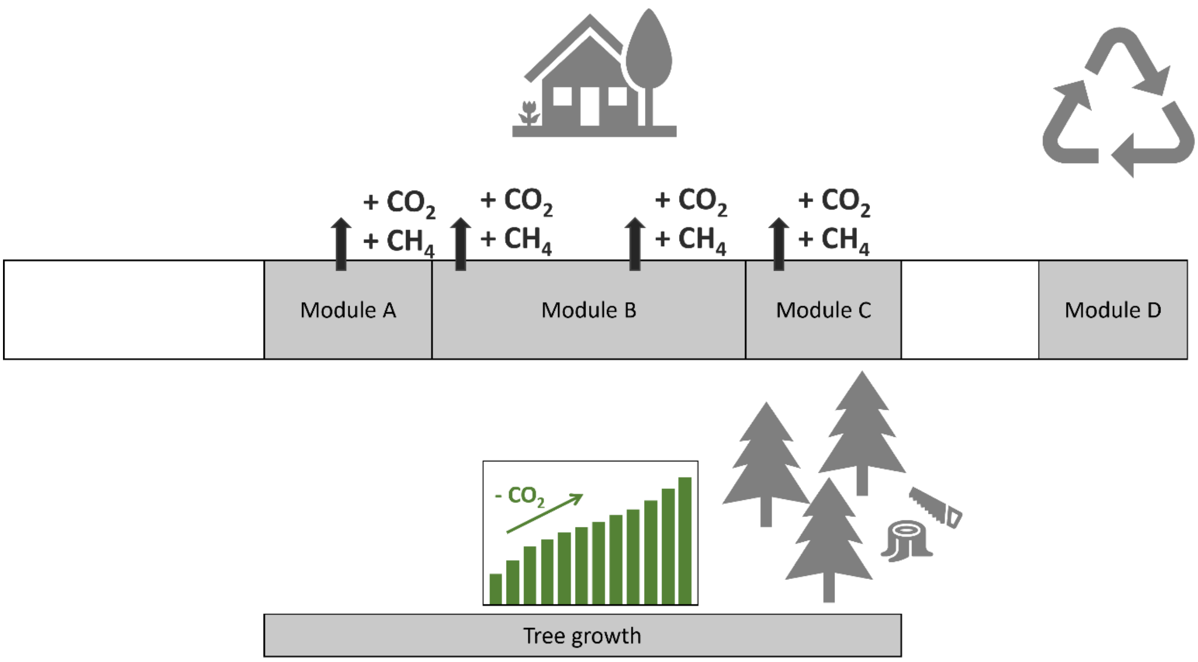


Figure 8 Schematic illustration of a dynamic approach through the life phases. In black fossil-based emissions are presented and in green, a hypothetical development of growing biomass during the life phases is shown as a bio-based credit.

4.3 Comparison of Approaches

In this chapter, three methods have been discussed, each having a different way to comprehend the biogenic carbon storage of bio-based materials. The first two methods have proven to be comparatively static, exhibiting no temporal differentiation across a product's lifetime. A benefit of the 0/0 method is that there is no need for extensive research into the stored carbon of a product. As a result, each product is easily comparable, and the potential of double counting or incorrect LCA design tuning is also reduced. On the contrary, the method leaves valuable data unconsidered and therefore deviates from reality. The -1/1 method does capture information concerning the stored biogenic carbon, even though no temporalities can be implemented through the life cycle of the product. This makes the separation between fossil-based emissions and bio-based emissions distinct. Subsequently, practitioners of LCAs can state these differences as a reason to select their product. Even though the method gives more information on the product, the results of an LCA will not differ from the 0/0 method. Additionally, when conducting an LCA for specific modules, the consideration of biogenic carbon makes it complicated, for module A, a subtraction would take place, and for module C, an addition of carbon. This could result in a more positive module A and a more negative module C. The LCA is therefore vulnerable to potentially mistaken interpretations of the results.

The dynamic approach considers all emissions to be time-dependent and therefore creates a more detailed representation of reality in the LCA. The approach creates the opportunity for a wide variety of applications concerning the temporalities of environmental harm. By considering every year separately within the time horizon a more realistic representation can be created. For materials containing biogenic carbon, the approach can create a benefit as the considered surface area in the GWP will be smaller for emissions taking place later on the time horizon. Bio-based materials often release large amounts of emissions at the end of their life cycle, as stored biogenic carbon is released. By creating a benefit for emissions occurring later in the life cycle, the use of bio-based materials is encouraged. Most importantly, the increased level of detail creates more reliable comparisons, even if, in certain scenarios bio-based materials score lower compared to traditional methods (Levasseur et al., 2010). With a dynamic approach, it becomes possible to model various temporal processes, such as land use change, which potentially creates lower results for bio-based products. On the other hand, temporal processes such as biomass growth can also be added, creating a potential benefit for bio-based materials. This temporal complexity makes it hard to find consensus on its potential effect on future LCAs. Still, a consensus is found in the valuation of increased detail in the life cycle of a product or process (Almeida et al., 2015; Levasseur et al., 2013; Levasseur et al., 2010).

5 Crediting Methods for Emission Timing

When executing LCAs, generally no crediting takes place for the storage of biogenic carbon or for delaying emissions. However, various crediting methods have been developed to create a benefit for materials or products that contain such aspects. The global warming potential (GWP), presented in Equation (1), will be used as the driving impact category for the crediting on a time horizon of 100 years. For simplicity, the comparisons are made solely based on CO_2 and therefore disregard other GHGs. Additionally, for each crediting method, the assumption is made that the used materials are equally replanted for future uses. In this chapter, three crediting methods will be discussed, illustrated, and compared.

Before elaborating upon the methods, the common notation for GWP crediting related to carbon storage will be presented. Regarding biogenic construction materials, the benefit and quantification of the climate benefits of stored biogenic carbon are deemed credits. In light of that, the GWP is influenced by this credit. As shown in Equation *(4)*, the GWP for bio-based materials consists of two separate components. First, the GWP_{bp} which obtains the GWP of a biogenic CO_2 pulse (BP), and second, the credit (C) gained from the storage of biomass for several years.

$$GWP = GWP_{BP} - GWP_C \tag{4}$$

5.1 Tonne-year Approaches

Two methods considered in this research apply a tonne-year approach, the Moura-Costa and Lashof methods for accounting for temporary carbon storage. Both methods are designed to provide a credit in mass CO_2 equivalent for withholding carbon from the atmosphere. Subsequently, this credit can be subtracted from GHG inventory to compensate for its effects in the LCA. For both of these methods, the Bern Model plays an important role in calculating the credit for delayed carbon emissions. By using a tonne-year approach, the emission is multiplied by the number of years, creating a tonne-year value. Subsequently, the tonne-year can be recalculated towards a mass, which is used as a credit. With consideration of the decay of $CO_{2,}$ the surface area under the Bern Model can be used to calculate the tonne-years of an emission.

5.1.1 Moura-Costa Method

One of the tonne-year approaches was introduced by Moura Costa & Wilson (2000). Originally, the method was developed to calculate the carbon sequestration and storage benefits of an afforestation project. However, the method also appeared to apply to biogenic carbon storage in the built environment. In Equation (5), the mathematical relationship of the Moura Costa method is presented.

$$GWP_{MC} = -GWP_c = -\begin{cases} \dfrac{C_0 * \alpha_{CO2} \int_0^{\tau} dt}{\int_0^{TH} \alpha_{CO2} * \gamma(t) dt}, & for\ \tau \le T_e \\ \dfrac{C_0 * \alpha_{CO2} T_{eTH}}{\int_0^{TH} \alpha_{CO2} * \gamma(t) dt}, & for\ \tau > T_e \end{cases} \tag{5}$$

It can be seen in the crediting equation that the GWP of the biogenic pulse emission is absent when crediting bio-based material using the Moura Costa approach. Due to the assumption of Moura Costa & Wilson (2000) that a biogenic CO_2 pulse emission is carbon neutral, the value of GWP_{BP} is zero and therefore absent. The resulting GWP is therefore only dependent on the negative crediting value. The outcome of this credit is dependent on two statements determined by the T_e, the equivalence time, and the storage time of the biogenic carbon, τ. Depending on the chosen time horizon, the method finds varying equivalence times calculated using the Bern Model. Moura Costa & Wilson (2000) determined that the equivalence time was reached when the surface area under the Bern Model over the time horizon was equal to the surface area of the equivalence time. As a time horizon of 100 years is commonly used, the equivalence time creates an equal surface area when 48 years of storage is reached. This means that if a unit of biogenic carbon is stored for 48 years, the same amount of credit can be assigned to the material. Using this, it is possible to calculate a linear credit per year of storage, also known as the equivalence factor or tonne carbon-year factor. After 48 years of storage, a maximum of one unit of carbon credit can be assigned. The authors argue that if an emission occurs after the time horizon, the equivalence time also remains the same, as the Bern Model does not change for a given time horizon. If the time horizon increased, the T_e would also increase, meaning that the required storage time to grant the same carbon credit would likewise increase.

In Figure 9, a visualisation of the equivalence time is presented by looking into the various surface areas using a time horizon of 100 years. In grey, the surface area underneath the Bern Model is presented. It is seen that with a pulse emission of a tonne, a value of 48 tonne-years is reached. In orange, the surface area is shown for delaying or sequestering a pulse emission with an equal pulse emission of a tonne of CO_2. By having a value of a tonne after 48 years of storage, the surface equals the surface area of the Bern Model. Meaning that if a pulse emission is delayed for 48 years, the benefit is equal to the entire pulse emission.

An example is illustrated for the crediting of carbon storage using the Moura Costa method in Figure 10. By using a time horizon of 100 years, the CO_2 equivalent in kg of crediting and the pulse emission is presented on the y-axis. The x-axis shows five scenarios with storage times: 0, 25, 50, 75, and 100 years. Without years of storage, no crediting should be considered, as there is no benefit concerning atmospheric carbon levels. For 25 years of storage, it is observed that for a tonne of CO_2 pulse emission, 520.83 kg of CO_2 is assigned as a credit using the Moura Costa method. For the considered storage times after 50 years, the crediting is equivalent to the entire pulse emission, as the equivalence time with a time horizon of 100 years is located at 48 years. The assumption of carbon neutrality causes the biogenic GWP for the material to score negatively, but if consideration is made of all fossil-based emissions, it may result again in a positive value for the total GWP.

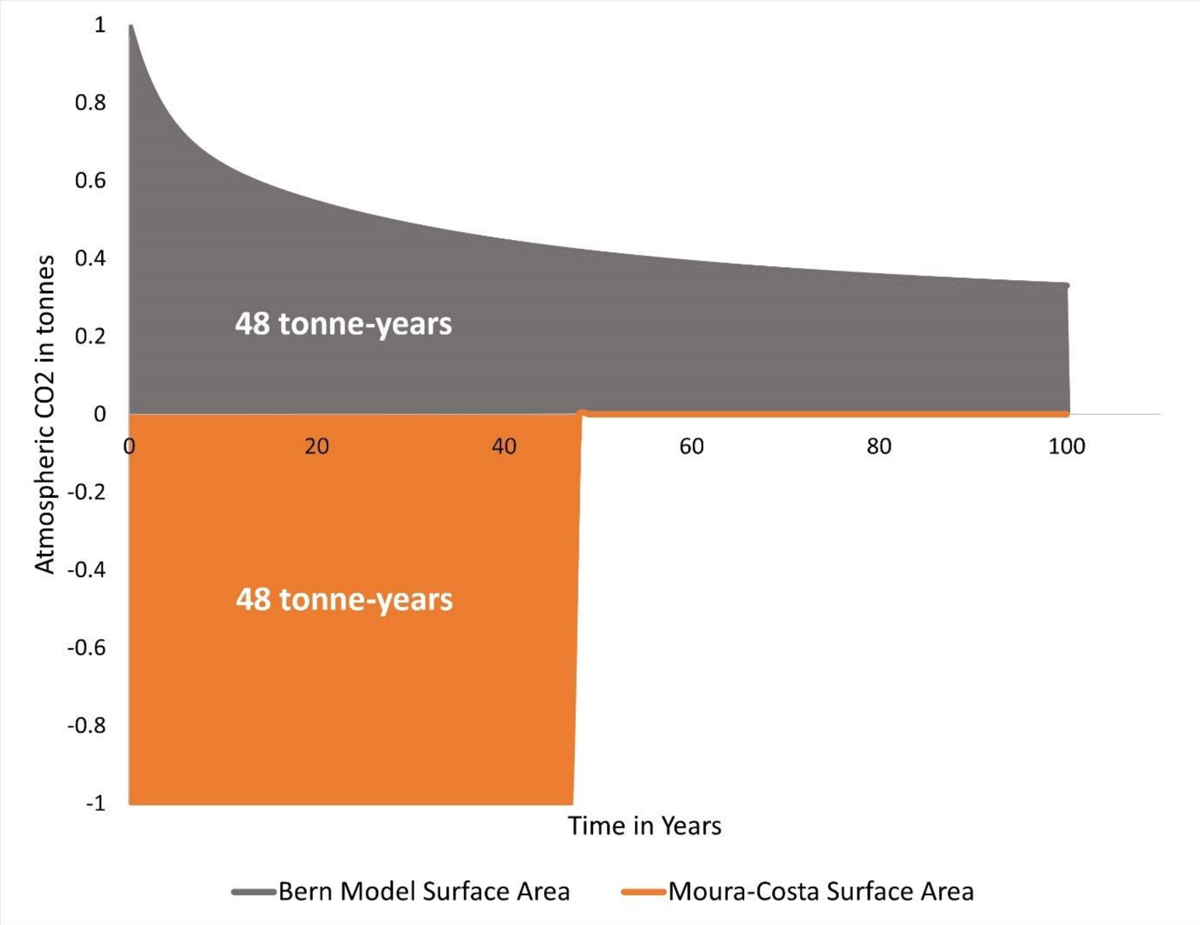


Figure 9 Illustration of the equivalence time of the Moura Costa crediting method. In grey, the surface area underneath the Bern Model is presented using a tonne pulse emission. In orange the surface area of the potential pulse emission delay and therefore its crediting is shown.

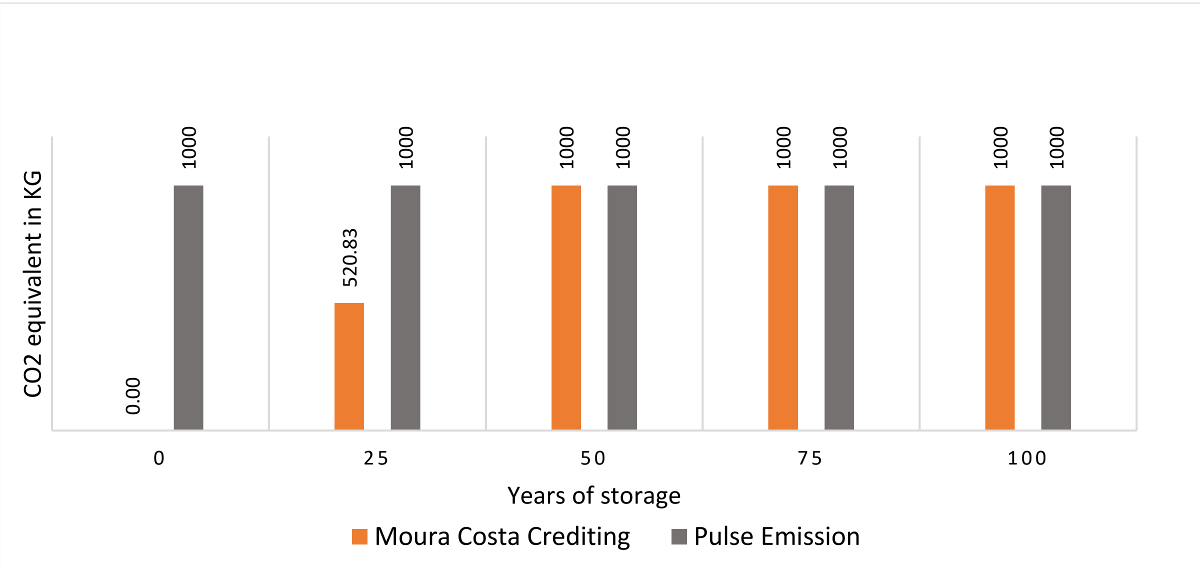


Figure 10 Crediting of biogenic carbon storage in kgs CO_2 equivalent using the Moura Costa method for the years of storage: 0, 25, 50, 75, and 100.

5.1.2 Lashof Method

The Lashof method (Fearnside et al., 2000) again uses the surface area under the Bern Model to calculate the benefit of delayed emissions. Different from the Moura-Costa method, it cannot credit the entire pulse emission before surpassing the time horizon. Only after storing the biogenic carbon for exactly the time horizon the total credit is equal to the initial pulse emission. In Equation (*6*), the mathematical approach of Fearnside et al. (2000) is presented.

$$GWP_{Lashof} = -GWP_c = \frac{C_0 \int_{TH-\tau}^{TH} \alpha_{CO2} * \gamma(t)dt}{\int_0^{TH} \alpha_{CO2} * \gamma(t)dt} \tag{6}$$

Similar to the Moura Costa method, the Lashof method assumes carbon neutrality concerning biogenic pulse emissions and therefore assigns a value of zero for GWP_{BP}. By integrating the CO_2 decay curve over the area that is outside the time horizon, a credit is created. As the storage of biogenic carbon causes the pulse emission to occur in a later year than year zero, the tail of the decay curve will shift outside the timeframe. Depending on the number of years of storage, the tail will differ in size. The longer the storage period, the further the curve will be from the initial timeframe. Subsequently, the surface area can be calculated, resulting in the corresponding credit. If the storage time is equal to the time horizon, the entire curve will be located outside the timeframe, resulting in a credit equal to the original pulse emission.

In Figure 11, an example is given where 75 years of delay is credited for a tonne CO_2 pulse emission. On the y-axis, the atmospheric CO_2 level is presented, showing the decay based on the Bern Model. The x-axis presents the timeframe, including the shifted pulse emission based on the delay of 75 years. For the entire pulse emission, a surface area of around 48 tonne-year can be found. When calculating the surface area outside the time horizon based on the shifted pulse emission, a value of 29.83 tonne-year is found. By dividing the surface area outside the time horizon by the entire surface area of the decay, a fraction of around 62% is found outside the timeframe, meaning that 62% of the initial pulse emission can be assigned as credit.

Additionally, in Figure 12, five storage times are presented with their corresponding credits. Again, by using a time horizon of 100 years, the CO_2 equivalent in kg of crediting and pulse emission is shown on the y-axis. The x-axis illustrates the five scenarios with storage times of 0, 25, 50, 75, and 100 years. It is observed that the crediting increases with the length of the storage time. However, It is hard to observe a clear trend in the crediting due to the limited number of examples. In Chapter 5.3, the trend of the Lashof crediting method will be discussed over the entire TH. Nonetheless, in Figure 12, it is observed that with 25 years of storage, a credit of 180.97 kg is reached, for 50 years, a credit of 390.25 kg, and for 75 years, a credit of 637.11 kg. For carbon storage over the entire time horizon, the entire pulse emission will be credited. Similar to the Moura Costa crediting method, the assumption of carbon neutrality causes the crediting to encapsulate the entire biogenic GWP.

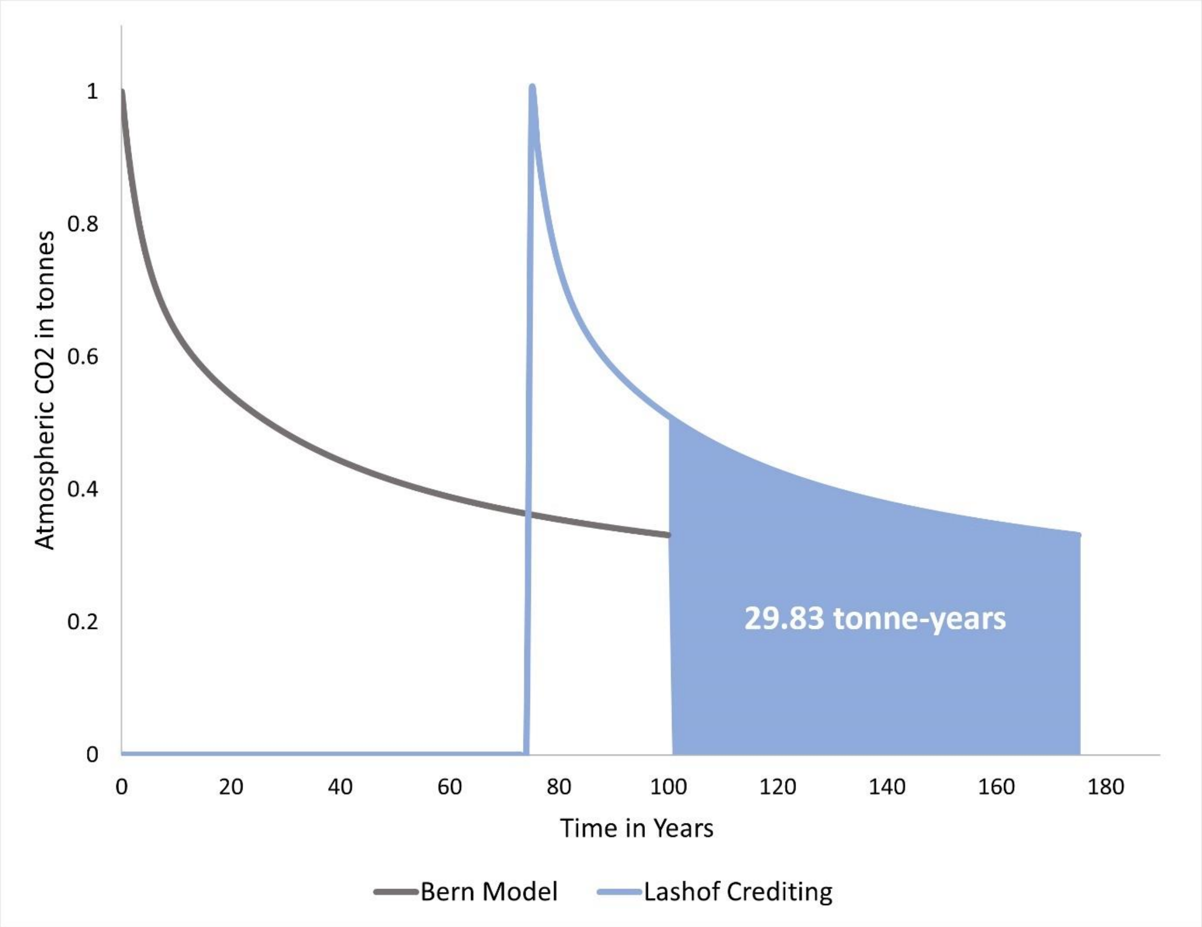


Figure 11 Illustration of the surface area outside the time horizon using a tonne pulse emission for 75 years of delay according to the Lashof crediting method.

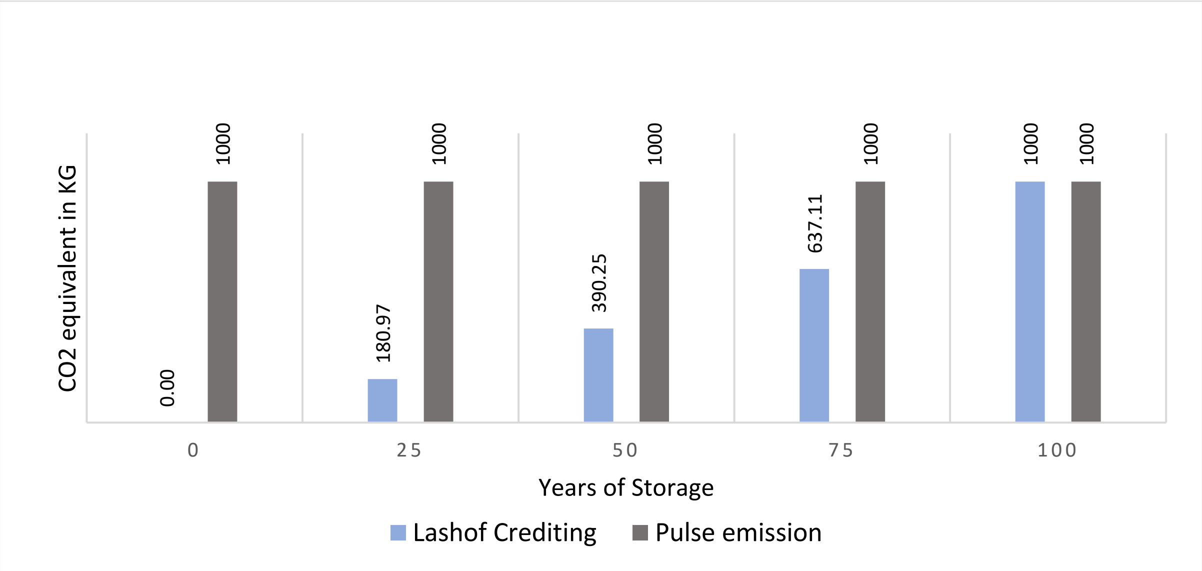


Figure 12 Crediting of biogenic carbon storage in kgs CO_2 equivalent using the Lashof method for the years of storage: 0, 25, 50, 75, and 100.

5.2 ILCD Handbook Method

Based on ISO 14040 (2006a) and ISO 14044 (2006b), the European Commission (EC) created the International Reference Life Cycle Data System (ILCD) (EC, 2010a). Before, the practitioner of LCAs was left with a wide range of choices. These choices are essential for the application of LCAs, as a diverse set of questions needs to be addressed and answered. However, to ensure the quality, consistency, and comparability of LCA data and studies, the European Commission (EC) created the ILCD. It consists primarily of the ILCD Handbook (EC, 2010a) and the ILCD Data Network (EC, 2010b). Especially the ILCD Handbook (EC, 2010a), where a series of technical documents that guide LCA practitioners are presented, will be discussed.

In the ILCD Handbook (EC, 2010a), an approach to account for temporal variabilities in GHG emissions in LCAs is presented. As most standards describe, temporary carbon storage and delayed emissions shall not be considered in the LCA as a default (Hoxha et al., 2020). However, exceptions can be made if the goal of the study justifies it, according to the ILCD Handbook (EC, 2010a). Assuming this is the case, both delayed emissions and carbon storage are to be assessed equally. The crediting value is based on the GWP comparison between the greenhouse gas in question and CO_2. When considering CO_2, per year of delay, the total emissions will decrease by a factor of 0.01, with a maximum of 100 years. A linear relation is assumed over the time horizon, which results in the following equation:

$$GWP_{ILCD} = -GWP_C = -\frac{C_0 \int_0^{TH} \alpha_{GHG} * \gamma_{GHG}(t)dt}{\int_0^{TH} \alpha_{CO2} * \gamma_{CO2}(t)dt} * (0.01 * \tau) \tag{7}$$

In Equation (7), it is again observed that carbon neutrality is assumed for bio-based construction materials and therefore excludes the pulse emission. When conducting the GWP calculation based on the ILCD Handbook, a time horizon of 100 years is generally adopted. Eventually, the credit can be calculated by multiplying the original GWP by the crediting factor of 0.01 and the number of years stored (τ). For emissions occurring beyond the TH, a new inventory is created called "long-term emissions" (EC, 2010a). These, are not part of the general LCIA results but have to be presented and discussed separately. For emissions occurring after 100,000 years, no consideration is expected using the method.

In Figure 13, the crediting of the ILCD method is presented for a time horizon of 100 years. On the y-axis, the CO_2 equivalent is presented in kg. Against the x-axis, the five scenarios of carbon storage are presented, with storage times of 0, 25, 50, 75, and 100 years. Again, a pulse emission of a tonne of CO_2 is used as a reference. It is observed that with a linear increase, the crediting reaches the entire pulse emission at τ = 100. For each step of 25 years, the credit increases by 250 kg of CO_2. For the biogenic GWP, due to the assumption of carbon neutrality, it will reach a value equal to the crediting calculated.

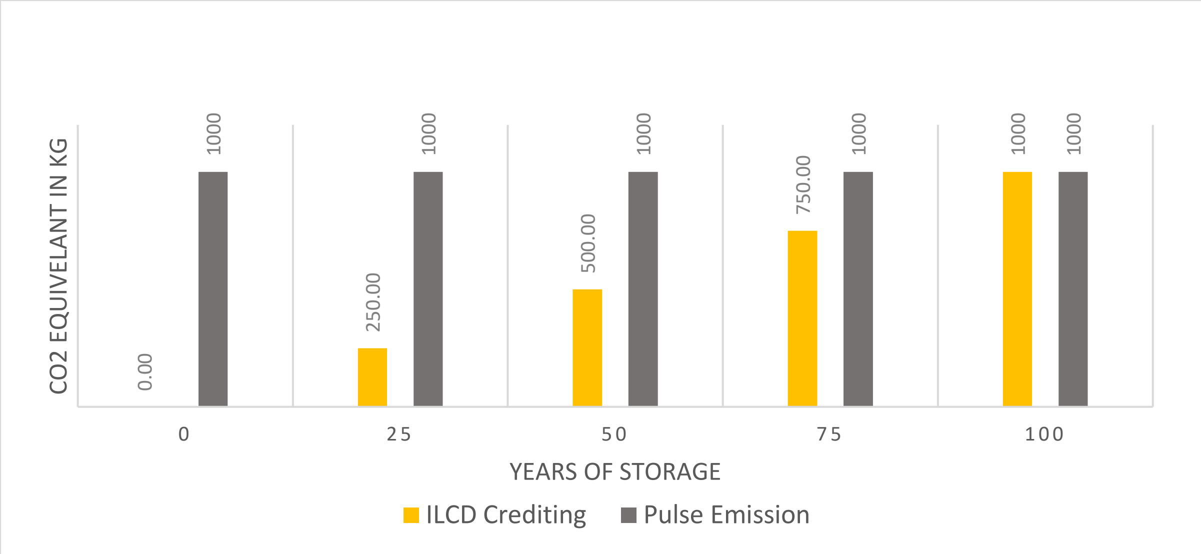


Figure 13 Crediting of biogenic carbon storage in kgs CO_2 equivalent using the ILCD method for the years of storage: 0, 25, 50, 75, and 100.

5.3 Comparison of Methods

Various methods were discussed that consider the benefits of biogenic carbon storage. Each method has its own underlying assumptions and considerations that could influence policymakers' preferences. Such preferences lie outside the scope of this research, but the properties of each method are aimed at being assessed. In Figure 14, the three methods are presented, compared to a fixed GWP without crediting. On the y-axis, the relative GWP is compared to the GWP without crediting. The x-axis shows the storage time in years. Generally, carbon neutrality is assumed for the GWP of bio-based materials, meaning that the biogenic pulse GWP is zero. In the figure, this is shown by the fixed GWP. The Moura-Costa method shows, with the strongest decline, that shorter storage time will have a stronger impact on the GWP. The ILCD method shows a constant decline, resulting in a linear decrease in the impact of the GWP. Lastly, the Lashof method shows a curved decline, resulting in a relatively stronger impact in the later years of the time horizon. This means that the longer the storage, the greater the relative impact.

An influential assumption each method makes concerns the time horizon. A commonly used time horizon is 100 years, as this fits the practical implantation of LCAs in the built environment and its policies (Guest et al., 2013). The lifetime of a building generally fits within this horizon, making it possible to create sufficient comparisons. Nonetheless, this assumption is very prominent in the conclusions drawn from the LCA results. When considering the crediting methods, changing the time horizon would change the impact of delaying emissions. For example, when considering a time horizon of 500 years for the Moura-Costa method, the equivalence time (T_e) would reach a value of 157 years instead of 48 (Moura-Costa & Wilson, 2000). Meaning that to reach the same credit a longer storage time would be necessary. Next to the Moura-Costa method, the Lashof and ILCD would likewise be influenced by the change in time horizon. This emphasises the relevance of the time horizon, and it is therefore needed to find a clear consensus on the suitability and influence of a specific horizon. Additionally, the considered crediting methods appear to assume carbon neutrality when calculating the GWP for bio-based construction materials. Even though this is a widely accepted assumption for approaching biogenic carbon, the consideration of this assumption could change the impact of the crediting methods. It is therefore necessary to create a clear view of the impact of such an assumption. In Chapter 4, the various approaches to biogenic carbon are presented and assessed for further elaboration on the topic.

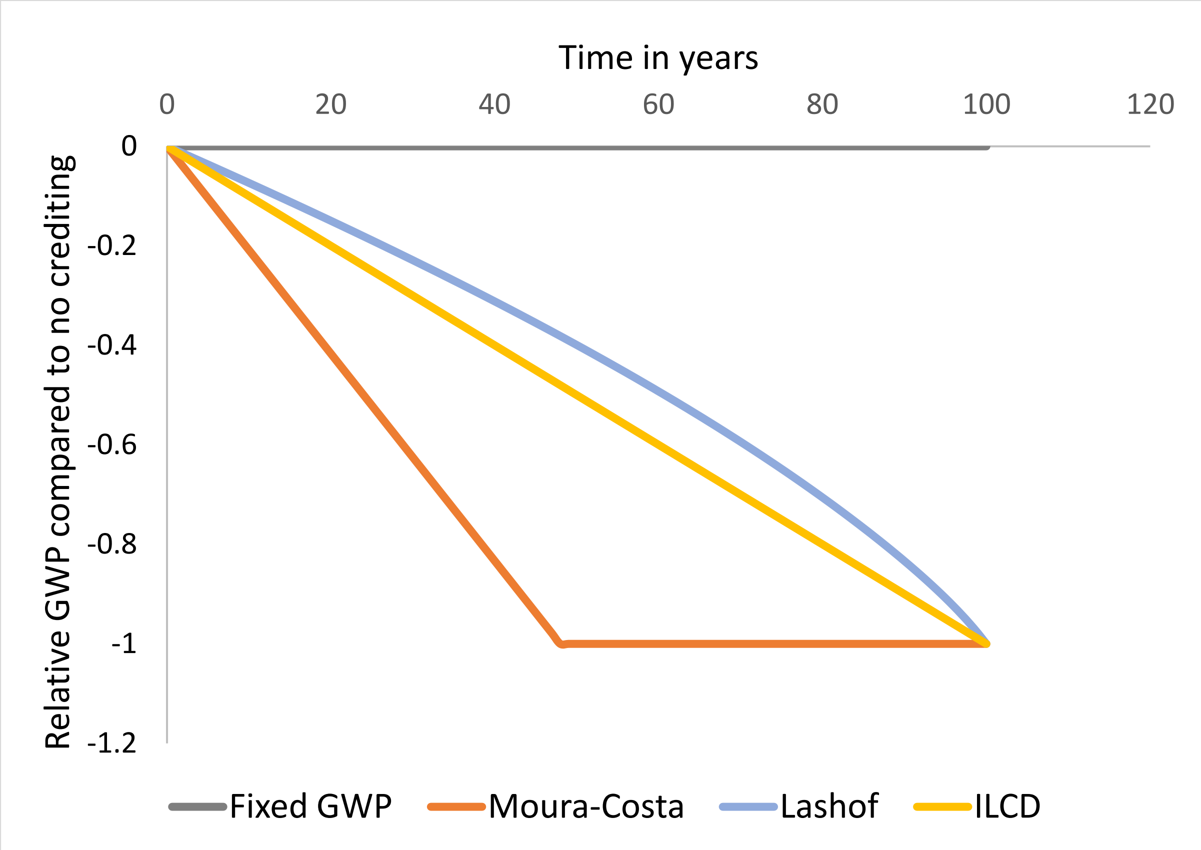


Figure 14 Visual representation of the four options considered for evaluating temporary carbon storage with a time horizon of 100 years.

The methods discussed have solely been focused on the delay of a biogenic pulse emission, but bio-based products have another influencing characteristic that is not considered: the aspect of regrowth or regeneration. Each bio-based product is regenerative and therefore contains a temporal effect that influences its benefit in the storage of biogenic carbon. The time of regrowth for each specific bio-based product creates a variety of benefits. For example, considering a tree with a regrowth time of more than 100 years, if this tree is used in a building with a lifetime of 100 years, the tree will not regenerate within this time. The biogenic carbon that is subsequently released at the end of life is not equal to the stored carbon during plant growth. Following the proposed crediting mechanism, the benefit would not consider this disbalance, which deviates from reality. On the contrary, a crop with a rotation time of less than 10 years is possible to regrow multiple times within the lifetime of the product, creating a much stronger benefit for such a crop. Guest et al. (2013) introduced a crediting method that takes into account the rotation time of a bio-based material to credit its biogenic carbon storage. From this method, it can be observed that depending on the time horizon and the rotation time, the crediting of biogenic carbon increases when the rotation time is less than the storage time. However, due to time constraints, the method of Guest et al. (2013) is not included in the analysis. Future research should include the considerations of rotation time while crediting biogenic carbon storage.

6 Current European Standards

The shape of a rectangular box, the procedures of doctors in health care, and many more processes and products follow specific standards to create equivalence through cultures, time, and geography (Timmermans & Epstein, 2010). The effectiveness and efficiency of our economy are supported by the standardisation of its processes and requirements (Shin et al., 2015). One of the most profound and large-scale organisations that provide standardisation on a global level is the International Organization for Standardization (ISO). This organisation creates international standards for the industry in various aspects of technology and manufacturing, placing them at the base of global construction. Next to this global level, the European Union (EU) created the European Standards, also known as the European Norm (EN). While the EN largely corresponds with the ISO standards, the implementation and regulation within the EU are more convenient. Lastly, on a national scale, each country has its own national standards and a responsible standardisation institute. In the Netherlands, standardisation is organised by the Royal Netherlands Standardisation Institute. All of these standards are developed and managed by various organisations, ensuring their actuality and quality. However, having such standards can counteract certain developments. The practicality of standards makes it difficult for them to enhance innovation, as they are designed to create uniformity rather than singularity. On each level of the standards, specific standardisation can be required through national or international law. In the Netherlands, for example, all levels of standardisation are present and enforced.

Considering LCAs, ISO created standards that describe the boundaries and possibilities when executing such assessments. Specifically, the ISO 14040 series has been developed to guide practitioners of LCAs and to create uniformity in the quantification of environmental harm. These standards are at the base of EN standards concerning LCAs. In the following chapter, the implemented standards concerning LCAs within the EU will be elaborated upon.

6.1 European Standards

In the construction industry, LCAs are commonly used to quantify the environmental performance of products and services. By using LCAs, it becomes possible to compare various building products and projects based on their environmental performance. The execution of these LCAs has to align with European Standards, otherwise, the comparison is less trustworthy and therefore jeopardised. The sustainability of a product or building is also dependent on its social, economic, technical, and functional performance. In Figure 15, the various categories of sustainable assessment are shown in the work program of CEN/TC 350 (2012). The CEN/TC 350 is responsible for the standardisation of sustainable assessment of new and existing construction works. The sustainability of these works is assessed not only based on their environmental performance but also on their social, economic, technical, and functional performance. In the figure, the organisational structure of the standardisation is presented according to these concept levels. Specifically, when considering the environmental performance of a building or construction material, the standards EN 15978 (CEN, 2012) and 15804 + A2 (CEN, 2019) are obligated throughout the EU. These standards will be assessed based on their ability to capture biogenic carbon and their temporal characteristics.

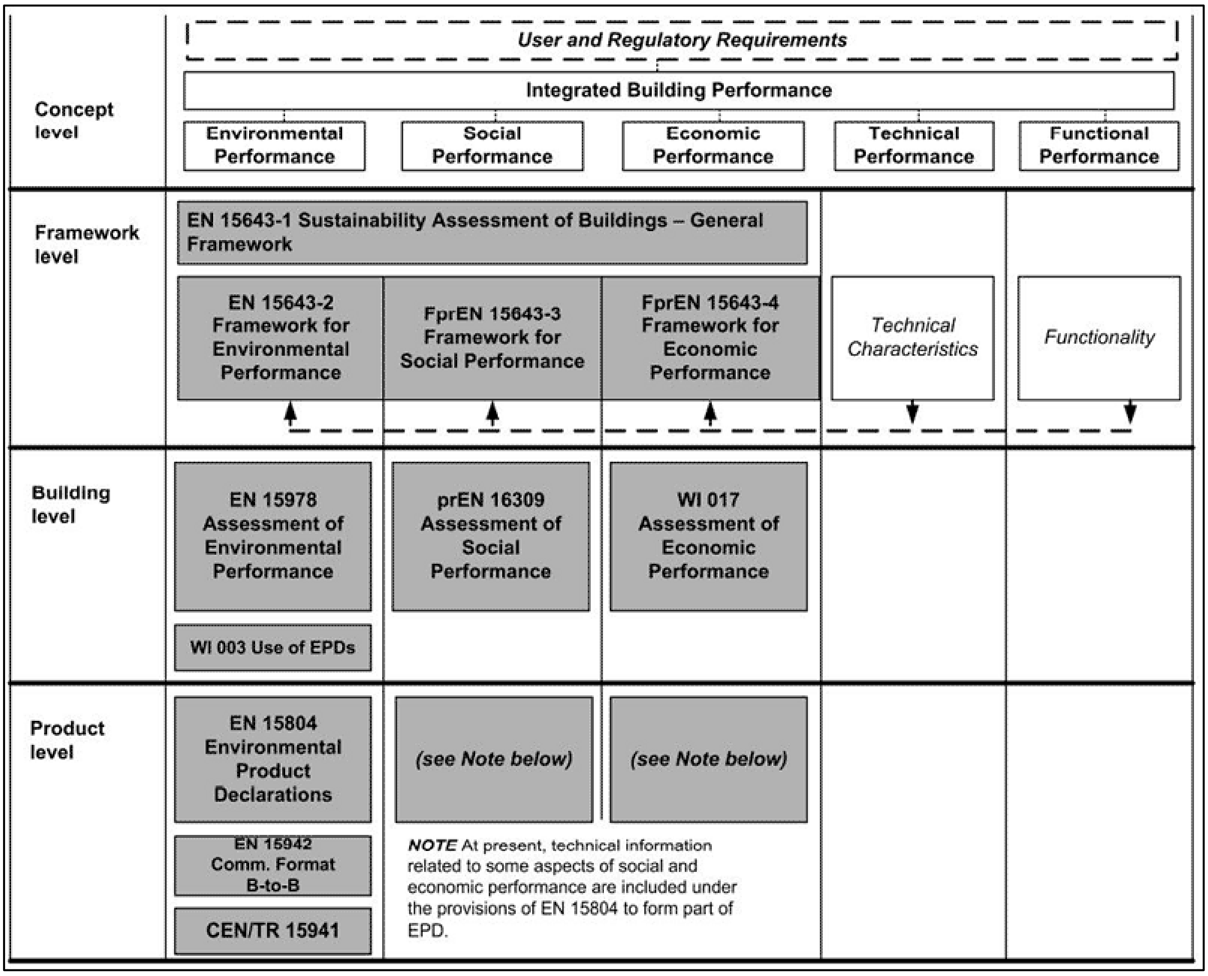


Figure 15 Work program of CEN/TC 350 (2012) containing the various concepts of sustainability in the built environment.

6.1.1 EN 15978 – Sustainability of Construction Works

The purpose of this standard, with the title "EN 15978 – Sustainability of construction works – Assessment of environmental performance buildings – Calculation method", is "to provide calculation rules for the assessment of the environmental performance of new and existing buildings" (CEN, 2012, p. 5). It is intended to provide guidelines on which documentation of environmental performance can be created and to support decision-making processes. As guideline, an exact representation of reality is neither mandatory nor feasible. Even though it is based on realistic scenarios, an estimate of reality is aimed for. The entire environmental performance of a building requires information from individual products and services, which are described in the standard EN 15804 +2 (CEN, 2019), which will be elaborated upon in Chapter 6.1.2. Nonetheless, the European standard 15978 (CEN, 2012) describes its scope as the following:

"This European Standard specifies the calculation method, based on Life Cycle Assessment (LCA) and other quantified environmental information, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment." (p. 6).

It provides a description of the object, the system boundaries, the procedure of inventory analysis, a list of indicators and corresponding procedures, requirements for presentation, and data requirements. In Figure 16, the different modules in the life cycle of a building are shown. Within the life cycle of a building, five stages can be distinguished. First, the product stages (A1 – A3) covers the 'cradle to gate' processes for materials and services. Second, the construction process stages (A4 and A5) encapsulate the transport to the construction site and the construction processes. Thirdly, the use stages (B1 – B7) covers the use, operational costs, and maintenance of the building in question. The fourth stage is the end-of-life stages (C1 – C4), where all the necessary processes of deconstruction are presented. Lastly, the fifth phase (D) adds information beyond the life cycle of the considered building, where the benefits and loads beyond the system can be added to the assessment.

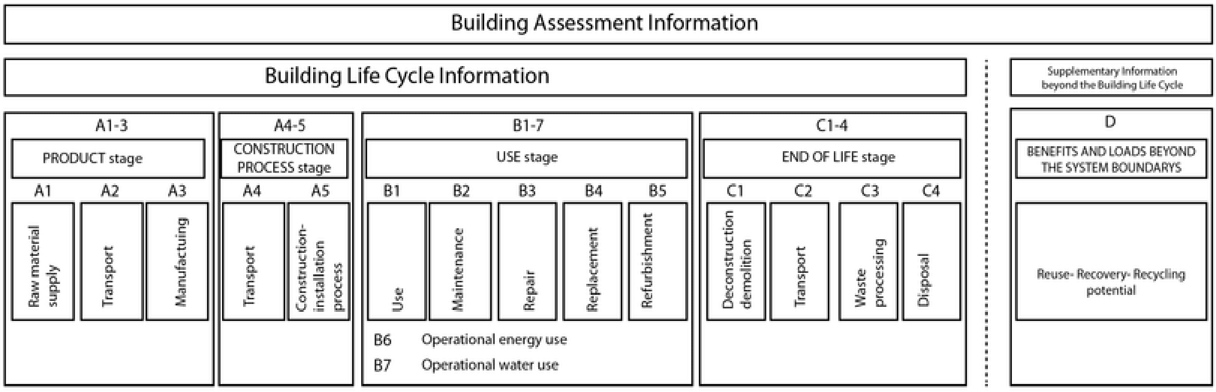


Figure 16 Display of different life stages of a building according to EN 15978 (CEN, 2012). For an enlarged version of the figure go to Appendix Figure 16 A.

Due to the larger scale of the standard, no mention of biogenic carbon is present. A remark is found concerning time-related aspects, stating that periodic operations are required to be described. Periodic operations such as maintenance, repair, and replacement need to be assessed throughout the life cycle. However, the timing of emissions or time-related environmental harm seems to be absent. There is clear mention of a time horizon of 100 years, which is considered appropriate for construction processes.

6.1.2 EN 15804 – Sustainability of Construction Works

EN 15804, with the title "Environmental product declarations – Core rules for the product category of construction products", is the European standard that provides product category rules (PCR) for all construction products and services. For an LCA on the product level, the standards describe environmental product declarations (EPD) as the means of communicating environmental information about a product. It transparently communicates objective, comparable, and third-party verified data about the products' LCA. The EPD functions as an overall view of a product and therefore contains summarised data from the initial LCA. By having PCRs, the standard creates a structure that ensures that all EPDs of construction products, services, and processes are derived, verified, and presented in a harmonised way. In 2019, the latest version (A2) of EN 15804 was published, adding a variety of chapters to the standard. Due to the renewal of the document, national governments need time to implement it. Resulting in older versions being complied with even though, in the future, the renewed standard will be leading.

Using the PCRs for construction products and services, environmental declarations are harmonised. It defines, describes, and includes a wide variety of details on the indicators, stages, rules, and conditions. Using these rules, an EPD will provide quantified environmental information for a construction product or service in a coordinated and scientific fashion. Using these EPDs, it becomes possible to create balanced comparisons throughout the construction works. The objective of the PCR and the standard is therefore to create verifiable and consistent data for an EPD.

6.1.2.1 Revised EN 15804 + A2

With the revised standard in 2019, six main differences can be noticed for EPDs in the construction industry. First, its ability to account for the benefits of end-of-life (EoL) recycling. The standard now offers calculations for the EoL and entails guidelines for these calculations. Using these, it becomes possible to calculate benefits and loads beyond the system boundaries. These benefits or loads are processes that are possibly related to a new product, therefore entering the boundaries of a new system and leaving its current one. Second, the reporting of biogenic carbon was introduced. Declaring biogenic carbon mass in the product and the packaging is now required in EPDs, creating a tool of comparison even though it is not necessarily credited in the methodology. It is expected that specifications of biogenic carbon contents will further crystalise in the Product's Environmental Footprint Category Rules, a new methodology that is under development by the EC. Third, the standard enforces specific configurations of life stages in EPDs. Modules A1–A3, C1–C4, and module D are required to be declared for all construction products. Depending on the scope of the LCA, different configurations of the modules are possible to present in the EPD. In Figure 17, the five possible options are presented to conduct an LCA according to EN 15804 + A2 (CEN, 2019). The figure shows in its columns the various life phases and in its rows possible configurations of these. Subsequently, in the cells, the life phases are presented as either mandatory, optional, or left empty. When the cell is empty, it means that it is not allowed to be included in the EPD according that option. For bio-based products containing biogenic carbon, it is not possible to execute a cradle-to-gate LCA. This is due to the assumption of carbon neutrality, specifically, the standards apply a -1/1 approach. If only module A were included in the LCA, an unrealistic negative value would be reached. Additionally, if module C is solely included, a wrongful estimation would be made as the biogenic carbon emissions are all added in this module. The fourth difference the standard brings is an addition to the environmental impact indicators. An important impact indicator that is used in EPDs is the global warming potential (GWP). The GWP gives the CO_2 equivalent of multiple GHGs and their impact on global warming. Previously, the GWP was a single indicator, but the A2 has created four different GWP indicators: the GWP-total, GWP-fossil, GWP-biogenic, and GWP-luluc. GWP-biogenic is solely the GHG originating from biogenic sources, and similarly, GWP-fossil is GHGs originating from fossil sources. The last indicator concerns land use and land use change (luluc), here the GWP of the land use and its changes is presented. Next to that, the weights of the impact indicators changed. For example, the impact category "resource depletion" is weighted more heavily, creating a stronger incentive for the development of a circular economy. Fifth, to create more uniformity in the documentation and data availability, the revised version will add changes in the quality assessment of data but, most importantly, require data to be stored in the ILCD format (EC, 2010a). The sixth change concerns the guidelines on how to describe functional and declared units. Creating the PCRs aims to create horizontal comparisons between production systems and therefore strengthen environmental comparisons throughout the sector. By following the renewed guidelines, products with similar functional units are now more accessible for comparison.

One of the changes in EN 15804 + A2 is the consideration of biogenic carbon. The incorporation of biogenic carbon is vulnerable to selecting specific modules to strengthen its effects on LCA results. To counteract this, any product that contains biogenic carbon is obligated to declare A1-A3, C1-C4, and D. This makes it impossible to use the storage of biogenic carbon as an advantage for the manufacturer of a product. When calculating the GWP, carbon offset processes, temporary storage, and delayed emissions are not mandatory to declare according to the guidelines of the standard. On the other hand, permanent biogenic carbon storage is not included in the calculation of the GWP. Although not being included in the GWP determination creates a benefit for such storage, it is still necessary to report such storage in the EPD separately. For temporary carbon storage, GWP-biogenic is used to account for the GWP concerning the GHG that is stored and emitted via biomass. Except for native forests, all carbon sequestered in living biomass in the product system is declared as GWP-biogenic.

When considering all the flows of biogenic carbon, the amount of CO_2 taken up in the biomass has to be equivalent to the amount emitted throughout its lifetime. This means that the net CO_2 emissions will always result in zero, and therefore the -1/1 approach is applied in the standard. Additionally, the standard specifically mentions that the biogenic carbon contents of a product or packaging are obligatory to declare if they contain more than 5% of its total weight.

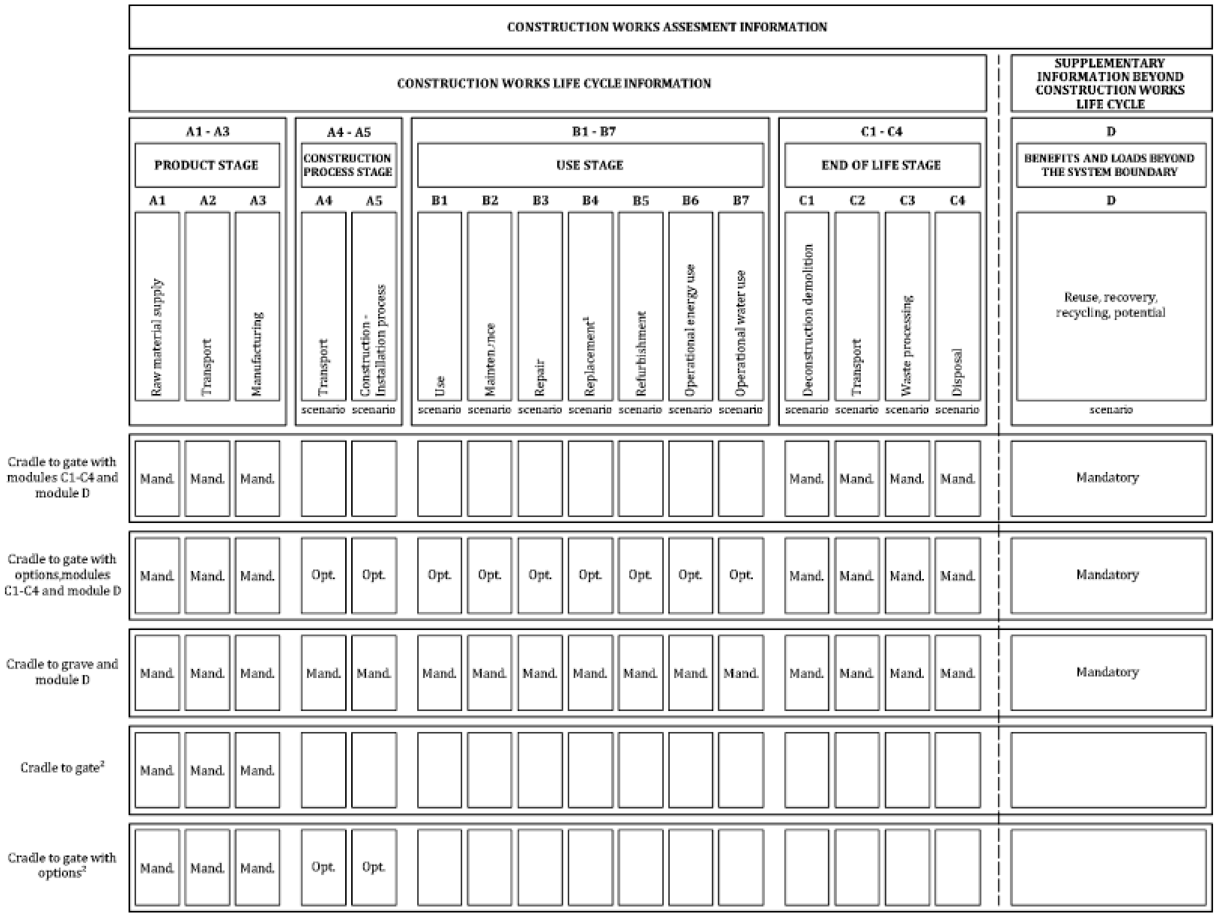


Figure 17 Representation of the possible configurations of life phases in EPDs according to EN 15804 + A2 (CEN, 2019). 1 replacement of components, parts, or systems. 2 is only possible if the conditions to exclude the declaration of modules C1-C4 and module D are met. For an enlarged version of the figure go to Appendix Figure 17 A.

7 Discussion

In the following chapter, the relationships, the relevance, and the limitations of the conducted study will be discussed. First, the relationship between the approaches to biogenic carbon, the potential crediting methods, and the European standards will be discussed. Second, the relationships between these findings and to the problem statement are presented and used to gain new insights into the complexity of the life cycle assessment (LCA) methodology. Third, the limitations of the research are discussed, and recommendations are made for future research.

7.1 Relationship between Biogenic Carbon, Crediting, and European Standards

The temporal complexity of LCAs is presented in three chapters: the approaches to capturing biogenic carbon within the methodology (Chapter 4), multiple crediting methods that credit the timing of emissions (Chapter 5), and the various standards with description of the considerations of biogenic carbon and emission timing (Chapter 6). Although each of them was discussed separately, the chapters contain several overlapping concepts that, when combined, create new insights.

First, in Chapter 4, the various approaches to biogenic carbon capture have been introduced and explained. The 0/0 and -1/1 methods appeared to be implemented most often due to their relatively simple implementations. After aggregation of the environmental impacts over the whole life cycle, the two methods result in the same value, yet differ through the life cycle phases. When considering the -1/1 approach, first a subtraction of the biogenic carbon storage takes place, followed by an emission at the end of its lifetime. This information, in contrast to the 0/0 method, can be used to understand and possibly give credit for the storage of biogenic carbon. In the research of Hoxha et al. (2020), it was observed that the 0/0 method was dominantly present in the literature. However, the -1/1 method is currently standardised by the European standards EN 15978 (CEN, 2012) and EN 15804 + A2 (CEN, 2019). The benefit of and reason for this standardisation is that the -1/1 method creates insights into the flows of biogenic carbon. Such details give the practitioner insights into the differences between fossil-based and bio-based emissions. Even in the absence of crediting mechanisms, this difference can guide the practitioner towards more bio-based materials. On the other hand, the second approach introduced was the dynamic LCA, a method that tries to assess temporality with more accuracy. Here, each year is considered separately instead of aggregating all emissions towards the start of the time horizon. Each emission is modelled from the moment of its emission until the end of the time horizon. This contributes to the level of detail within the LCA, but also with an increased complexity. Currently, the dynamic approach is particularly used within academia but is absent from practical implementation or within the applied standards of the EU. An important aim of standardisation is to create uniformity and simplicity throughout the sector. For the application of a dynamic approach, the complexity can conflict with these aims. The LCA practitioner needs to be able to easily use the methodology, which makes relatively abrupt changes in the standards difficult to implement. For all approaches, no crediting mechanisms are in place for the timing of emissions. However, the dynamic approach can implement temporal crediting by assessing each year separately. Which potentially makes it a valuable tool in the future.

Subsequently, different crediting methods were discussed, explaining the considerations and effects of each particular one in Chapter 5. All methods considered biogenic pulse emissions to be carbon neutral, meaning that it was assumed during growth that an equal amount of biogenic carbon was stored as the emitted carbon at the end-of-life (EoL). This assumption of carbon neutrality can be answered by both the 0/0 approach and the -1/1 approach, as both approaches do not affect the final result of the LCA while using the crediting mechanisms. Each crediting method applies to any time horizon, but due to the standardised value of 100 years, the methods have been applied to similar time horizons. One of the three crediting methods was the ILCD crediting method, where a linear crediting is applied, resulting in a credit equal to the entire biogenic pulse emission at the end of the time horizon. With a longer time horizon, the strength of the credit per year decreases. Similarly, when considering the Moura-Costa and Lashof methods, the time horizon also influences the results of the LCA. Again, with a longer timeframe, the strength of the credit decreases. Therefore, it is necessary to get consensus on an appropriate time horizon before establishing a crediting mechanism in the methodology. By further investigating the effects of the time horizon and its role in the LCA methodology, it is possible to reach such consensus. On the other hand, the dynamic approach to biogenic carbon uses a different mechanism to comprehend the temporalities in LCAs. The implementation of the method is correlated with an increase in complexity, making it difficult to implement. However, the approach itself contains the possibility of crediting without having to add a separate calculation. Due to its ability to assess each year separately, it is possible to credit each year for specific temporal aspects. For example, the growth of a bio-based product can easily be credited by subtracting the stored carbon per year from the global warming potential (Levasseur et al., 2010). Again, consensus is needed on the time horizon, but also consideration of this growth brings uncertainties. With the growth, the credit can be added beforehand if the material is grown before construction or during the lifetime of the product. If a dynamic approach would be applied, including the growth of bio-based materials, additionally consensus is needed on the corporation of growth. By either applying the growth before construction or during construction, a risk is created that the stored biogenic carbon is counted multiple times for different products, as their consideration of time can differ. Still, the method is able to comprehend temporality and the benefits of bio-based materials to a greater extent than the currently applied methodology.

In Chapter Current European Standards , the applied standards within the EU were discussed, specifically the standards EN 15978 (CEN, 2012) and EN 15804 + A2 (CEN, 2019). In these standards, the -1/1 approach for biogenic carbon was presented and standardised through the application of LCAs. The standards appeared to have no mention or method for the crediting of carbon storage, delay, or timing of emissions. With the revised version of EN 15804 (2019), one important addition was the changed documentation of LCA data. Here, the ILCD format for data collection and storage is made mandatory, creating uniformity and comparability throughout the methodology. Given that the ILCD crediting technique was presented that complies with these data criteria, an argument for the use of this crediting method is present. The crediting mechanism is only applicable in specific situations and is not implemented in the general execution of life cycle assessments. But when combined with the mandatory reporting of biogenic carbon contents, the crediting mechanism can be relatively easy to implement within the existing standards. Consequently, it holds significant relevance for future policymaking.

7.2 Relevance to the Problem Statement

The current state of our climate and resource depletion demands global change, and the EU aims to respond accordingly. However, the complexity of enacting the imagined response in a global environment remains significant. The findings of this study relate to this aim and its enactment, in the following sub-chapter, these relations are elaborated upon and used to better understand the context of the LCA methodology. Specifically, the relation between the environmental goals of the EU, the Doughnut and circular economies, end-of-life and time horizons, European standards, and the political complexity of LCAs will be discussed.

Temporary carbon storage gives time for technological innovations and progress, avoids radiative forcing for the given time, and part of the stored carbon may become permanently stored (Brandão et al., 2013). Additionally, sequestering carbon reduces atmospheric levels of carbon, therefore reducing the risk of exceeding possible environmental tipping points (Fearnside, 2008). Regardless of these potential benefits, the effectiveness of mitigating climate change through non-permanent carbon sequestration is extensively questioned (Kirschbaum, 2006; Meinshausen & Hare, 2000; Anderson & Peters, 2016). For example, by decreasing atmospheric CO_2 concentrations, the gradient between the atmosphere and other carbon sinks is decreased, creating less prominent differences and therefore lower carbon capture (Brandão et al., 2013). Subsequently, when the stored carbon is released, higher levels of carbon are reached in the atmosphere than when the atmospheric carbon was released before the storage. There is less natural carbon sequestration, and because of a sudden and extensive pulse emission, the carbon concentration increases rapidly, resulting in a higher net concentration. Even though these arguments are strongest when talking about large-scale carbon capture, they emphasise the importance of further research on the potential effects of substantial temporary carbon storage and natural carbon sequestration. On the other hand, the EU aims for a circular economy in the year 2050 (Domenech & Bahn-Walkowiak, 2019), meaning that reuse and recycling will be more prominent. Therefore, a scenario could be created where less incineration of bio-based products is present. This would prevent pulse emissions that cause a higher concentration at the EoL, thus creating a significant benefit for biogenic carbon storage in construction materials. Subsequently, the permanent storage of biogenic carbon will possibly increase further, as it creates a stronger incentive to build with bio-based materials. Another potential benefit of building with bio-based materials is that the infrastructure and technological processes are expected to improve in the future (Van der Giesen et al., 2020). This will create improved LCA results for bio-based materials, as common processes such as manufacturing and transport will be more efficient and therefore less harmful to the environment. Because these technological improvements are often considered definite (Buyle et al., 2019), it is a limitation that the LCA methodology does not take them into account. Various studies have attempted to address this constraint, but none of the suggested solutions has been applied in practice (Buyle et al., 2019; Wender et al., 2014).

Additionally, the construction industry seemed to be designed on the basis of capitalism, aimed at continuous growth (Wells, 1984). The LCA methodology is focused on traditional approaches to construction and economic systems, and therefore resulted in a relatively linear application. However, as addressed by Raworth (2017), this idea of continuous growth is outdated and unsuited for issues concerning global warming. To be able to sustain society within the boundaries of the ecological ceiling and the social foundation, the goal of continuous growth needs to be changed (Raworth, 2017). Raworth (2017) introduced this concept as the Doughnut Economy, shown in Figure 1. The LCA methodology could be considered a tool for quantifying the proximity of certain products to this ecological boundary. The results of the LCAs can tell the practitioner if the product or building is located within these boundaries or if it surpasses them. Currently, the methodology is unable to quantify the effect on the social foundation. However, to determine, for example, the effectiveness of a housing project, the social foundation is an influential component in the decision-making process. The inclusion of the social aspects in the LCA methodology is however developing and emerging through literature (Martínez-Blanco, 2015; Jørgensen, 2013; Hunkeler, 2006), making it a promising prospect for the quantification of social boundary in the Doughnut Economy. Ideally, this aspect would be included in the methodology, creating a quantitative measurement that encapsulates the environmental harm and the social components. However, to truly be located between the boundaries of the Doughnut Economy, degrowth needs to be realised. If the LCA methodology is used to create a stationary state, it can be expected that current environmental and social boundaries will remain imbalanced.

Next to the absence of a social foundation, the LCA methodology is also unable to fully capture circularity (Larsen et al., 2022). While the Doughnut Economy can function hand in hand with a circular economy, circularity within the LCA methodology appears to be complex (Haupt & Zschokke, 2017). Especially the end-of-life (EoL), where the reuse and repurposing of a product are credited, is influential for bio-based products. For bio-based products, this potential improvement of the LCA methodology could decrease the largest influencing phases of the life cycle as biogenic carbon emissions are released in the EoL. However, when considering circularity, the EoL of each product is linked to the first module of the subsequent life cycle. This makes the assessment of material more complex, but literature is available where circularity is implemented in the methodology (Larsen et al., 2022; Van Stijn et al., 2022). However, further research is necessary to assess the implementation of circularity in LCAs and its relation with biogenic carbon and crediting of bio-based materials.

The EoL has a strong influence on the LCA results of bio-based materials. Even without consideration of circularity in LCAs, the EoL generally contains the highest emissions of the life cycle for bio-based materials and is therefore of importance in the assessment. When assessing today's construction projects, the EoL remains a highly uncertain aspect of the LCA (Sandin et al., 2014), as demolition and disposal of construction materials are often expected to take place in 50 to 100 years (Frijia et al., 2011). While taking place in the distant future, the nature of these processes is unpredictable due to technological change and changing factors, such as climate pressures and the political field. If, it is decided in this distant future, to lengthen the lifetime of a bio-based product or to recycle it, the consideration of biogenic carbon and its crediting in the LCA changes. In addition, the choices of recycling, such as incineration or landfilling, also influence the results of an LCA. Incineration has benefits as bioenergy can be generated, but all stored biogenic carbon is released again into the atmosphere while landfilling can lead to fractional permanent storage of atmospheric carbon in the biosphere (Micales & Skog, 1997). These uncertainties contribute to the complexity of approaching biogenic carbon within LCAs and will influence decision-making based on these results. Further research is necessary to comprehend the various scenarios in the EoL and their effect on the LCAs related to the approaches of biogenic carbon and emission timing.

To achieve uniformity, consistency, comparability, and to counteract complexities such as the EoL, standards are implemented within the EU on European and national level. The value of these standards is frequently questioned due to their nature to counteract innovation, but commonly, the positives are considered higher than the negatives (Shin et al., 2015; Vollebergh & Van Der Werf, 2014; Allen & Sriram, 2000). Still, when considering small-scale innovation, standards can counteract its success. This is due to the scale on which standardisation takes place (Pelkmans & Renda, 2014). By capturing a wide range of users, the room for innovative developments is tightened. Regarding the standards EN 15978 (CEN, 2012) and EN 15804+A2 (CEN, 2019), where the European standardisation of LCAs is presented, the freedom for innovation is relatively small. The standards create uniformity and comparability throughout the sector, but if innovative processes are implemented, the translation into the LCA can be difficult. Governmental organisations must judge adherence to their regulations, therefore creating a boundary for innovative processes. However, certain aspects that started as innovations are now considered necessary or normal. For example, the reporting of biogenic carbon contents. Previously, when the 0/0 approach was still considered sufficient, no reporting of biogenic carbon contents was presented in environmental product declarations (EPDs). However, currently, it is considered normal to provide such information and the absence of this data is in violation of the standards. Due to environmental pressures, the reporting of biogenic carbon is obligatory, and potentially, using a similar route, the crediting of this storage can be accomplished as well. Considering the revised version of EN-15804 (+A2), which was published in 2019, the described extra requirements are despite the environmental benefit currently not enforced in the Netherlands. Even though the standards will become obligatory, the effects of global warming are rapidly increasing, and especially in a sector where a relatively long development time is common, this delay in implementation is undesirable. The findings of this research and therefore the future implementation of crediting mechanisms in the methodology need to be considered within a more immediate timeframe. Innovative solutions could potentially answer the need for climate adaptation by designing crediting mechanisms for the storage of biogenic carbon. However, these innovations have to be able to develop into functioning mechanisms, which emphasises the need for flexibility in the standards.

Various approaches to biogenic carbon storage and methods of crediting the timing of emissions have been discussed in this paper. Yet, to make recommendations, their characteristics are not necessarily decisive for policymakers. With the pressures of climate change, crediting mechanisms can improve the accuracy of the method. However, to decide which crediting mechanism is preferable, a wide range of factors are considered by policymakers. Deciding in what way the method is implemented throughout Europe is strongly dependent on political, ideological, and ethical values (Finnveden, 1997). From the different crediting methods assessed, various differences can be observed, with the most influential one being the strength of the credit. For example, the Moura Costa method is a relatively strong crediting method where, after 48 years of storage, the initial pulse emissions are compensated. On the other hand, the ILCD is a comprehendible method where, for each year of biogenic carbon storage or delay, a one per cent compensation takes place. Lastly, the Lashof method is in between, using a similar method as the Moura Costa but having a crediting strength more like the ILCD methodology. The exact characteristics of the various crediting methods are explained in Chapter 205, and their trend over time is shown in Figure 14. However, some approaches may be preferred over others based on the pressures of our political, ideological, and ethical ideals. Potentially, the implementation of the Doughnut Economy could change the future application of crediting methodologies. For example, if this concept is considered common practice, the importance of correctly quantifying the proximity of the ecological boundary is strengthened, making crediting mechanisms more likely to be implemented in the LCA methodology. On the other hand, changes in the LCA methodology can influence various parties in the sector, creating interest from a wide range of stakeholders. This makes policymaking and the creation of standards vulnerable to lobbying in the sector. However, to correctly suggest the reasoning behind decision-making, further research is necessary to better understand the organisational structure and influences.

7.3 Limitations of the Research

Throughout the research, the temporal complexity of LCAs is commonly considered. Due to this complexity, the study was unable to capture all considerations related to it but was able to answer valuable components that contribute to the understanding of the temporal influences within the methodology. Still, the research leaves limitations in its methodology and the deliberation of its results. The following section will start with an elaboration of the methodology with corresponding limitations and recommendations, and ends with the limitations and recommendations of the results.

To get a comprehensive understanding of the effect of each approach to biogenic carbon or crediting method, a practical comparison could be a beneficial addition to this research. Currently, the study is focused specifically on the methodology, demonstrating how changes in the methodology affect the LCA results of bio-based materials. This gives a clear overview of the effect of changing the methodology, but the relationship between the practical implementation is rather limited. When applying a larger-scale comparison based on a case study, such relationships are easier to find. Additionally, comparisons can be made with traditional materials to gain knowledge of the differences between these materials in their characteristics and position within the methodology. For future research, a case study analysis would be a valuable tool to better understand the practical effects of the methodological choices presented in the research. The various components considered within the LCA methodology were based on literature, although the method is mostly executed in practice. The method is scientifically grounded but is used outside the scientific context. Approaching it from a methodological perspective is legitimate from a scientific point of view, but when assessing the practical benefits of such methodological changes, the scientific approach can deviate from reality. Due to this, it is suggested that for future research, more consideration be given to the practical obstacles within the bio-based construction industry. A potential approach to such a direction could be an interview-based analysis of the potential and obstacles of bio-based construction materials.

With such an analysis, producers of the material, practitioners of LCAs, and policymakers are potential interviewees.

Considering the approaches to biogenic carbon, the dynamic approach showed the potential to capture significant temporalities throughout the life cycle of a product. Dynamic LCAs are a relatively new subject but show promising results, making them a fast-growing scientific topic (Anand & Amor, 2017). Due to its capability to assess each year separately, it becomes possible to include all sorts of temporal processes, such as capturing crediting mechanisms, within the methodology. Another potential benefit of the dynamic LCA is that it gives insight into the yearly emissions of the entire construction sector. By having this, it can become clear for governments which year is potentially a year with a lot of emissions and therefore interesting to attempt to reduce. Because of that, it is recommended to further investigate the potential for translating the beneficial characteristics of bio-based products in a dynamic way. As the dynamic approach may be able to encompass temporality to such an extent that no crediting is necessary through the methodology.

Still, the crediting methods are a valuable tool to create realistic and objective assessments of life cycles. For this study, the aim was to capture the temporal benefit of storing carbon within the material in question, but bio-based products have another characteristic that is currently not used in the assessment. Bio-based products have a regrowth time that fluctuates per crop and therefore also per material, which influences their temporal characteristics. An example of a method where such temporalities are part of the crediting mechanism is that of Guest et al. (2012). This method uses the crop rotation time to create a benefit based on the duration of the material stored. For example, when considering a type of timber that has a rotation time longer than the storage time, the crediting methods described in Chapter 5 would still be able to give the entire pulse emission as a credit. The crediting method of Guest et al. (2012) would result in a lower credit because the entire tree has not yet grown back. On the other hand, if the product has a very short rotation time, the entire pulse emission would be credited in an equally short period of time. This makes the crediting method suitable to capture bio-based temporalities while creating a transparent comparison based on their rotation periods. The implementation of such a method is correlated with in an increase of complexity in the methodology, which is not always preferable. Potentially, to limit this complexity the method of Guest et al. (2012) could be implemented solely in the inventory of timber or other crops with generally longer rotation periods. However, future research should be conducted to better understand the mechanism and potential benefits of a crediting method like this one.

Regarding the assessed standards in this study, a clear focus was on the currently applied European standards. However, the improvement of standards is an ongoing process, and there are presently various initiatives and developments further enhancing the methodology. The standards that are currently being developed were not within the scope of this research. This is potentially a missed opportunity concerning the practical relevance of the research. By looking into standards that are currently under development, the research was possibly able to pinpoint specific aspects that are related to the research. Therefore creating a stronger influence on future decision-making. Nonetheless, by looking into the current standards, a better understanding is created of the present implementation and the corresponding shortcomings of bio-based materials. Additionally, the research was aimed specifically at European Standards, while it is common for other national or international standards to be active in the industry. On the national level, due to their smaller scale, it might be possible to have more room for innovative initiatives. Potentially, by looking into these, certain mechanisms to credit emission timing or biogenic carbon storage can be found. Further research is necessary to look into the different standards and give a better description of the current field and its corresponding standards.

8 Conclusion

It is commonly accepted that current environmental pressures demand sustainable global practices. An important method to quantify these sustainable practices is the LCA methodology, where various environmental impact categories are assessed over the lifetime of a product or service. Within the construction industry, material-based environmental harm is substantially influencing the climate. With these increasing pressures, the industry faces significant challenges in its processes and uses. One of its challenges is the use of bio-based construction materials that contain biogenic carbon storage and regenerative characteristics. Specifically, the translation of these materials and their characteristics into the LCA methodology is considered a shortcoming. A characteristic of bio-based materials is the storage of biogenic carbon, where atmospheric carbon is stored in the material. This can potentially mitigate climate change, but the LCA methodology appears to lack credit for this benefit. Additionally, the methodology currently assesses all emissions over the life cycle of a product as if they occurred at the same time, but the environmental harm of an equal emission at the end of the life cycle is less harmful than one at the start. For bio-based materials, the later stages of the life cycle, when stored biogenic carbon is released, contain more emissions compared to traditional construction materials. Currently, no differentiation takes place for this temporal difference in the LCA methodology, which is a missed opportunity to emphasize sustainable practices.

With regard to LCAs of bio-based construction materials, the goal of this study was to determine the effects of biogenic carbon approaches and crediting mechanisms for the timing of emissions on LCA results. Based on these, and the applied European standards, a comprehensive study was conducted on the current state of the LCA methodology and potential changes in the future. One of the key findings of the study was that the temporal complexity of bio-based materials concerns various components that influence the results of an LCA. In this research, three methods of biogenic carbon storage were considered. First, based on a static approach, the 0/0 method and the -1/1 method apply the traditional methodology, where no temporal difference is applied over the emissions. Here, both methods assume carbon neutrality for bio-based materials and result in the same final LCA result. However, the -1/1 method uses the stored biogenic carbon as a subtraction in the first phase and an addition in the last phase of the life cycle. The method, therefore, accounts for and reports the storage of biogenic carbon but gives no credit for its presence. The third method argued from a dynamic approach is the dynamic LCA. In this method, each year is individually assessed for its own emissions, instead of aggregating all emissions. This brings a level of complexity, but also the possibility of having a detailed assessment of a product and potentially room for specific crediting per year. Each approach has characteristics that influence its complexity and implementation in practice. If simplicity is the aim, the 0/0 method appears best, but if the level of detail is to be the highest, the dynamic method is most suited. Currently, within European standards, the -1/1 method is practised, as it contains more detail than the 0/0 approach and is less complex than the dynamic LCA.

Subsequently, three crediting methods for the timing of emissions were elaborated upon. Specifically, the crediting of the delay of emissions, often related to biogenic carbon storage, was explained. First, the Moura-Costa method was presented. The method has the strongest crediting compared to the other methods and was able to credit the entire biogenic pulse emission after 48 years of storage. For the crediting before 48 years, a linear relation was used to credit the storage. If the storage time exceeded 48 years, the credit would remain equal to the single biogenic pulse emission. Second, the Lashof method, where an exponential relationship was used to determine the crediting. Here, the total pulse emission was credited after storing the biogenic carbon for 100 years, or equal to the time horizon. The storing of biogenic carbon in the later years of the life cycle is credited more than in the earlier years of the life cycle due to its exponential nature. Third, the ILCD method assumes a linear relationship over the entire time horizon. When using a time horizon of 100 years, the crediting would equal 1 per cent of the pulse emission per year of storage. Each method used a time horizon of 100 years and assumed carbon neutrality in its calculation. The use of the time horizon influences the results of each crediting method, and it is therefore important to be precise and transparent with its usage. Within the European standards, no mention of carbon crediting was found, but the ILCD methodology is currently used as a dataset formatting requirement. The ILCD crediting method is mentioned as only being used in specific studies but is easily accessible and useable for future practitioners of LCAs. Therefore, with a relatively simple crediting mechanism, the method appears to be suitable and easily accessible to credit biogenic carbon storage.

Due to the given limitations, the research is unable to recommend a single approach for biogenic carbon storage or a crediting mechanism for the timing of emissions. However, due to the current climate pressures, it can be concluded that a change in the LCA methodology is preferable. Specifically for bio-based materials, crediting for biogenic carbon storage could promote the use of bio-based construction materials and therefore mitigate the material-based emissions of the industry. Yet, to decide on a biogenic carbon approach or crediting method, the practical and political obstacles and motives have to be investigated. Answering this complexity of implementing and changing the LCA methodology is of value to strengthen the argumentation and recommendations for specific alterations in the method. By looking into a potential case study comparison, the perception of these complexities could be clarified, and a better understanding of material-based characteristics could be gained. Additionally, such a comparison could contribute to the comparison of traditional construction materials and bio-based materials. This can influence the decision-making concerning material choices and, therefore, the environmental impact of the industry.

Finally, it can be concluded that the current LCA methodology is unable to capture temporalities specific to bio-based materials, which is a deviation from reality and the current aim of policymakers. To improve the methodology, consideration of crediting for biogenic carbon and emission timing has to be made, as the need for reduced material-based emissions in the industry asks for bio-based materials.

9 References

Allen, R. H., & Sriram, R. D. (2000). The role of standards in innovation. *Technological Forecasting and Social Change*, *64*(2-3), 171-181.

Almeida, J., Degerickx, J., Achten, W. M., & Muys, B. (2015). Greenhouse gas emission timing in life cycle assessment and the global warming potential of perennial energy crops. *Carbon management*, *6*(5-6), 185-195.

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renewable and sustainable energy reviews*, *67*, 408-416.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182-183.

Arehart, J. H., Hart, J., Pomponi, F., & D'Amico, B. (2021). Carbon sequestration and storage in the built environment. *Sustainable Production and Consumption*, *27*, 1047-1063.

Bahramian, M., & Yetilmezsoy, K. (2020). Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). *Energy and Buildings*, *219*, 109917.

Berge, B. (2009). *The ecology of building materials*. Routledge.

Brandão, M., Levasseur, A., Kirschbaum, M. U., Weidema, B. P., Cowie, A. L., Jørgensen, S. V., ... & Chomkhamsri, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *The International Journal of Life Cycle Assessment*, *18*, 230-240.

Buyle, M., Audenaert, A., Billen, P., Boonen, K., & Van Passel, S. (2019). The future of ex-ante LCA? Lessons learned and practical recommendations. *Sustainability*, *11*(19), 5456.

CEN (2012). EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. *European Committee for Standardization.*

CEN (2019). EN 15804:2012+A2 sustainability of construction works - environmental product declaration - core rules for the product category of construction product. *European Committee for Standardization.*

CEN/TC 350. (2012). Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (EN 15804:2012+A1:2013). *European Committee for Standardization.*

Di Maria, A., Eyckmans, J., & Van Acker, K. (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste management*, *75*, 3-21.

Domenech, T., & Bahn-Walkowiak, B. (2019). Transition towards a resource efficient circular economy in Europe: policy lessons from the EU and the member states. *Ecological Economics*, *155*, 7-19.

EC (2010a). ILCD Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps. *Publications Office of the European Union. (Report No. JRC58190)*, European Commission

EC (2010b). ILCD Data Network - Compliance Rules and Entry-Level Requirements. *Publications Office of the European Union. (Report No. JRC58193)*, European Commission

EC (2015). Communication the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. *COM/2015/0614 final*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614 (accessed 13 March 2023).

Fearnside, P. M. (2008). On the value of temporary carbon: a comment on Kirschbaum. *Mitigation and Adaptation Strategies for Global Change*, *13*, 207-210.

Fearnside, P. M., Lashof, D. A., & Moura-Costa, P. (2000). Accounting for time in mitigating global warming through land-use change and forestry. *Mitigation and adaptation strategies for global change*, *5*(3), 239-270.

Finnveden, G. (1997). Valuation methods within LCA-Where are the values?. *The International Journal of Life Cycle Assessment*, *2*, 163-169.

Frijia, S., Guhathakurta, S., & Williams, E. (2012). Functional unit, technological dynamics, and scaling properties for the life cycle energy of residences. *Environmental Science & Technology*, *46*(3), 1782-1788.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm? *Journal of cleaner production*, *143*, 757-768.

Guest, G., Cherubini, F., & Strømman, A. H. (2013). Global warming potential of carbon dioxide emissions from biomass stored in the anthroposphere and used for bioenergy at end of life. *Journal of industrial ecology*, *17*(1), 20-30.

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of industrial ecology*, *19*(5), 765-777.

Hafner, A., Ott, S., & Winter, S. (2014). Recycling and end-of-life scenarios for timber structures. *Materials and Joints in Timber Structures: Recent Developments of Technology* (pp. 89-98). Springer Netherlands.

Hartley, K., van Santen, R., & Kirchherr, J. (2020). Policies for transitioning towards a circular economy: Expectations from the European Union (EU). *Resources, Conservation and Recycling*, *155*, 104634.

Haupt, M., & Zschokke, M. (2017). How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. *The International Journal of Life Cycle Assessment*, *22*, 832-837.

Houghton, J. T., Meira Filho, L. G., Bruce, J. P., Lee, H., Callander, B. A., & Haites, E. F. (Eds.). (1995). *Climate change 1994: radiative forcing of climate change and an evaluation of the IPCC 1992 IS92 emission scenarios*. Cambridge University Press.

Hoxha, E., Passer, A., Mendes Saade, M. R., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., & Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings & Cities*, *1*(1), 504-524.

Hunkeler, D. (2006). Societal LCA methodology and case study (12 pp). *The International Journal of Life Cycle Assessment*, *11*, 371-382.

ISO (2006a). Environmental management – Life cycle assessment – Principles and framework. *(ISO Standard NO. 14040:2006)*, International Organization for Standardization.

ISO (2006b). Environmental management – Life cycle assessment – Requirements and guidelines. *(ISO Standard NO. 14044:2006),* International Organization for Standardization.

Jørgensen, A. (2013). Social LCA—a way ahead?. *The International Journal of Life Cycle Assessment*, *18*, 296-299.

Kirschbaum, M. U. (2006). Temporary carbon sequestration cannot prevent climate change. *Mitigation and Adaptation Strategies for Global Change*, *11*, 1151-1164.

Larsen, V. G., Tollin, N., Sattrup, P. A., Birkved, M., & Holmboe, T. (2022). What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. *Journal of Building Engineering*, *50*, 104203.

Levasseur, A., Lesage, P., Margni, M., & Samson, R. (2013). Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *Journal of Industrial Ecology*, *17*(1), 117-128.

Levasseur, A., Lesage, P., Margni, M., Brandão, M., & Samson, R. (2012). Assessing temporary carbon sequestration and storage projects through land use, land-use change and forestry: comparison of dynamic life cycle assessment with ton-year approaches. *Climatic change*, *115*, 759-776.

Levasseur, A., Lesage, P., Margni, M., Deschenes, L., & Samson, R. (2010). Considering time in LCA: dynamic LCA and its application to global warming impact assessments. *Environmental science & technology*, *44*(8), 3169-3174.

Martínez-Blanco, J., Lehmann, A., Chang, Y. J., & Finkbeiner, M. (2015). Social organizational LCA (SOLCA)—a new approach for implementing social LCA. *The International Journal of Life Cycle Assessment*, *20*, 1586-1599.

Meinshausen, M., & Hare, B. (2000). Temporary sinks do not cause permanent climatic benefits. achieving short-term emission reduction targets at the future's expense. *Greenpeace background paper*.

Micales, J. A., & Skog, K. E. (1997). The decomposition of forest products in landfills. *International Biodeterioration & Biodegradation*, *39*(2-3), 145-158.

Microsoft Corporation. (2012). *Microsoft Excel*. Retrieved from **https://office.microsoft.com/excel**

Morris, F., Allen, S., & Hawkins, W. (2021). On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. *Building and Environment*, *206*, 108285.

Moura Costa, P., & Wilson, C. (2000). An equivalence factor between CO2 avoidedemissions and sequestration–description andapplications in forestry. *Mitigation and adaptation strategies for global change*, *5*(1), 51-60.

Ness, D. A., & Xing, K. (2017). Toward a resource-efficient built environment: A literature review and conceptual model. *Journal of Industrial Ecology*, *21*(3), 572-592.

Pahl, S., Sheppard, S., Boomsma, C., & Groves, C. (2014). Perceptions of time in relation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(3), 375-388.

Pelkmans, J., & Renda, A. (2014). Does EU regulation hinder or stimulate innovation?.

Pittau, F., Krause, F., Lumia, G., & Habert, G. (2018). Fast-growing bio-based materials as an opportunity for storing carbon in exterior walls. *Building and Environment*, *129*, 117-129.

Pittau, F., Lumia, G., Heeren, N., Iannaccone, G., & Habert, G. (2019). Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. *Journal of Cleaner Production*, *214*, 365-376.

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., ... & Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, *68*, 333-359.

Raworth, K. (2017). Doughnut economics: seven ways to think like a 21st-century economist. *Chelsea Green Publishing.*

Röck, M., Baldereschi, E., Verellen, E., Passer, A., Sala, S., & Allacker, K. (2021). Environmental modelling of building stocks–An integrated review of life cycle-based assessment models to support EU policy making. *Renewable and Sustainable Energy Reviews*, *151*, 111550.

Sala, S., Amadei, A. M., Beylot, A., & Ardente, F. (2021). The evolution of life cycle assessment in European policies over three decades. *The International Journal of Life Cycle Assessment*, *26*, 2295-2314.

Sandin, G., Peters, G. M., & Svanström, M. (2014). Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. *The International Journal of Life Cycle Assessment*, *19*, 723-731.

Shin, D. H., Kim, H., & Hwang, J. (2015). Standardization revisited: A critical literature review on standards and innovation. *Computer Standards & Interfaces*, *38*, 152-157.

Skullestad, J. L., Bohne, R. A., & Lohne, J. (2016). High-rise timber buildings as a climate change mitigation measure–A comparative LCA of structural system alternatives. *Energy Procedia*, *96*, 112-123.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of business research*, *104*, 333-339.

Solomon, S., Qin, D., Manning, M., Averyt, K., & Marquis, M. (Eds.). (2007). Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC *(Vol. 4). Cambridge university press.*

Timmermans, S., & Epstein, S. (2010). A world of standards but not a standard world: Toward a sociology of standards and standardization. *Annual Review of Sociology, 36,* 69-89.

Van Der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, *259*, 120904.

Van Stijn, A., Eberhardt, L. C. M., Jansen, B. W., & Meijer, A. (2022). Environmental design guidelines for circular building components based on LCA and MFA: Lessons from the circular kitchen and renovation façade. *Journal of Cleaner Production, 357,* 131375.

Vollebergh, H. R., & Van Der Werf, E. (2014). The role of standards in eco-innovation: Lessons for policymakers. *Review of Environmental Economics and Policy*.

Wells, J. (1984). The construction industry in the context of development: a new perspective. *Habitat International*, *8*(3-4), 9-28.

Wender, B. A., Foley, R. W., Hottle, T. A., Sadowski, J., Prado-Lopez, V., Eisenberg, D. A., ... & Seager, T. P. (2014). Anticipatory life-cycle assessment for responsible research and innovation. *Journal of Responsible Innovation*, *1*(2), 200-207.

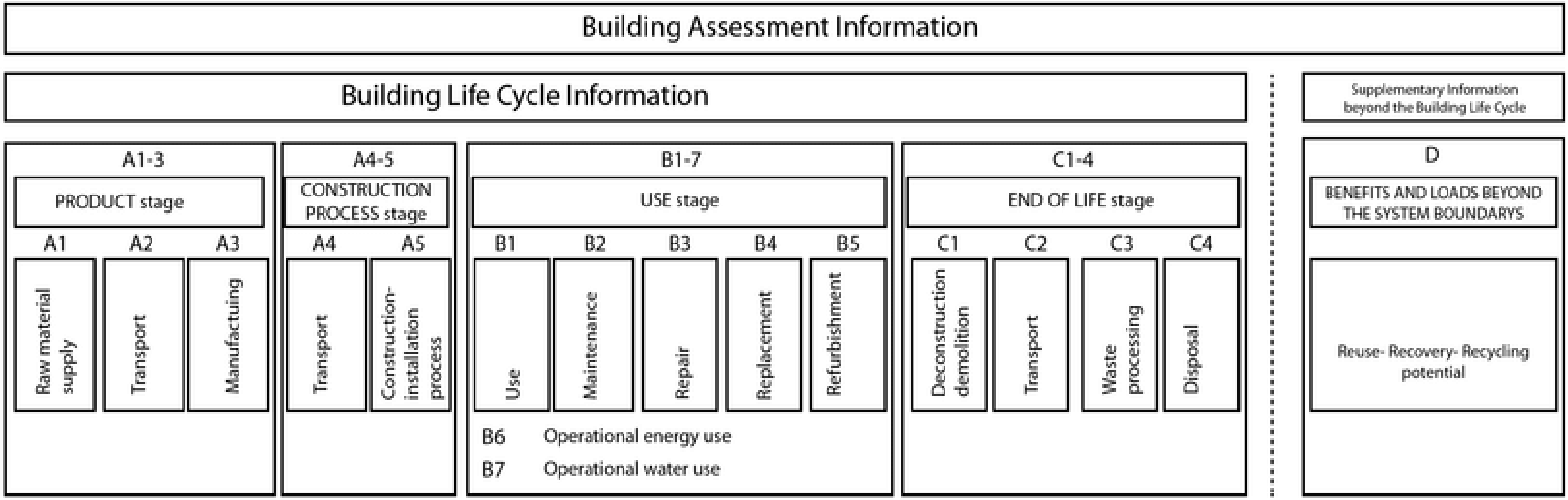
Whittemore, R., & Knafl, K. (2005). The integrative review: updated methodology. *Journal of advanced nursing*, *52*(5), 546-553.

Worrell, E., Price, L., & Martin, N. (2001). Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. *Energy*, *26*(5), 513-536.

Wu, P., Xia, B., & Zhao, X. (2014). The importance of use and end-of-life phases to the life cycle greenhouse gas (GHG) emissions of concrete–a review. *Renewable and Sustainable Energy Reviews*, *37*, 360-369

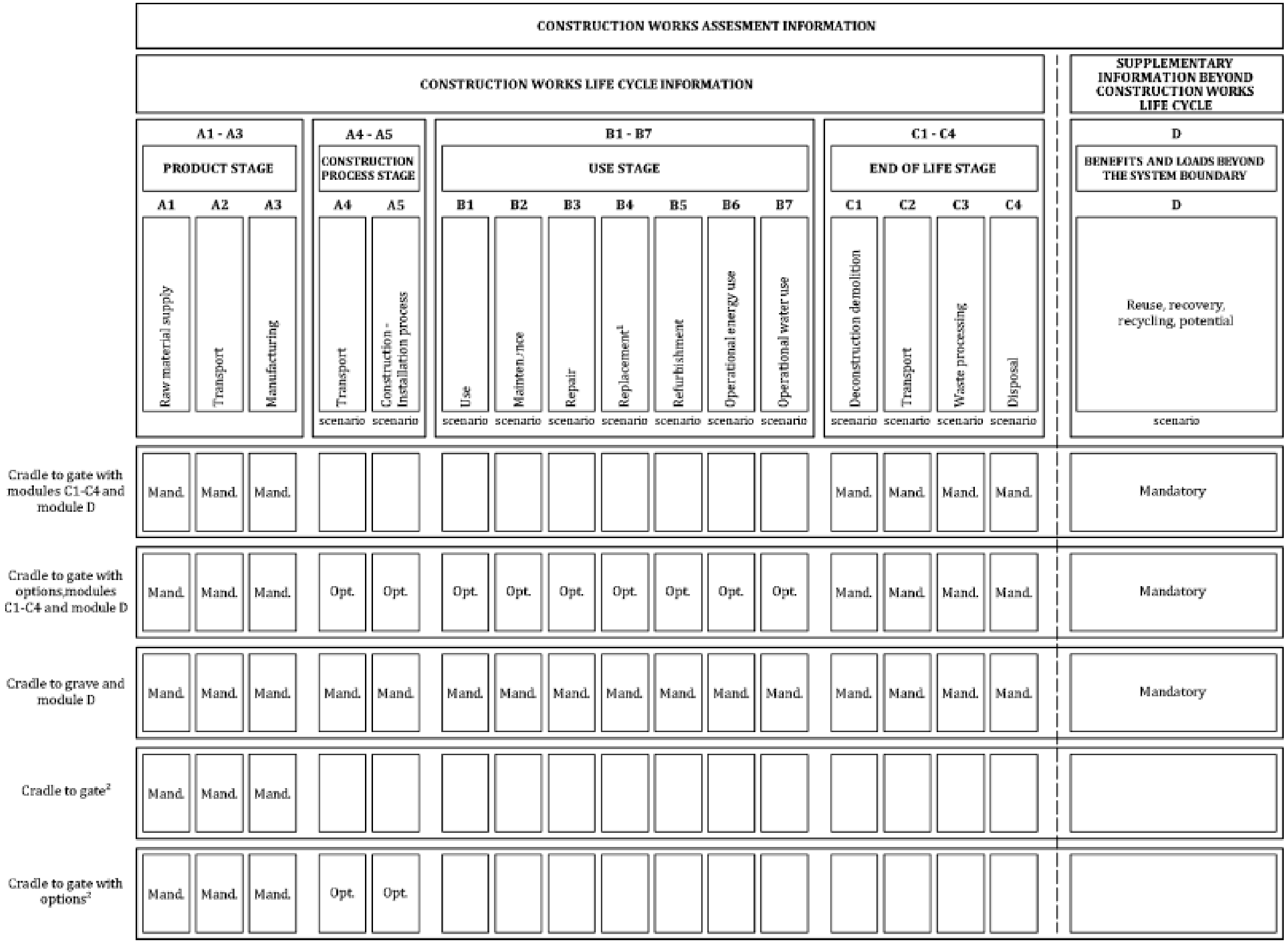
10 Appendix

10.1 Figure 16A



Appendix Figure 16 A Display of different life stages of a building according to EN 15978 (CEN, 2012).

10.2 Figure 17A



Appendix Figure 17 A Representation of the possible configurations of life phases in EPDs according to EN 15804 + A2 (CEN, 2019). [1] replacement of components, parts, or systems. [2] is only possible if the conditions to exclude the declaration of modules C1-C4 and module D are met.