

Dynamic Life Cycle Assessment of Reused Structural Timber: The Influence of Life Cycle Assumptions and Wood Species

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Master's dissertation submitted in order to obtain the degree of Master of Science in Engineering: Architecture - Architectural Design and Construction Techniques

Academic year 2025-2026

Preface

This master's dissertation marks not only the end of an intensive year of research, but also the completion of my studies. Throughout these years, I gradually developed a strong interest in sustainable and circular construction, and in the role that material choices can play in reducing the impact of the construction sector on climate change and the environment. This thesis provided me with the opportunity to further explore these interests through the topic of reused structural timber.

In this preface, I would like to thank several people who supported and guided me throughout this journey, and especially during the past year. I would first like to express my sincere gratitude to my supervisor, prof. dr. ir. arch. Marijke Steeman, for introducing me to the theme of life cycle assessment, for giving me the opportunity to work on this research topic, and for the guidance and valuable feedback throughout this project. I also want to warmly thank my advisors, ir. arch. Katrien Devos and David von Dufving, for their support, enthusiasm, critical insights, and continued involvement during the development of this thesis.

Next, I wish to thank my parents for their unconditional support throughout my studies and for giving me the opportunity to pursue this education. I also want to thank my brothers for their encouragement over the years.

In addition, I would like to thank my friends, both from my hometown and the many new people I met during my time in Ghent. All of them contributed in their own way to a period of my life that I will always look back on fondly.

In particular, I want to thank Kobe, not only for always being there and listening to countless hours of frustration and doubt related to this research, but also for all the evenings that helped me temporarily forget about my thesis altogether.

I would also like to thank Kyra for the many hours spent together in the library and for the much-needed breaks and moments of levity during the writing process. Furthermore, I want to thank Chiara for helping me take my mind off the research whenever returning home and for proofreading this thesis.

Finally, I hope this thesis can contribute, even in a small way, to the ongoing discussion surrounding the role the construction sector can play in creating a more sustainable built environment.

Killian

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Elk ander gebruik valt onder de bepalingen van het auteursrecht, in het bijzonder met betrekking tot de verplichting de bron uitdrukkelijk te vermelden bij het aanhalen van resultaten uit deze masterproef.

25 May 2026

Killian Geenens

This master's dissertation is part of an exam. Any comments formulated by the assessment committee during the oral presentation of the master's dissertation are not included in this text.

Deze masterproef vormt een onderdeel van een examen. Eventuele opmerkingen die door de beoordelingscommissie tijdens de mondelinge uiteenzetting van de masterproef werden geformuleerd, werden niet verwerkt in deze tekst.

Abstract

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Abstract

The construction sector is responsible for approximately 40% of global greenhouse gas emissions, increasing the interest in circular and biobased construction materials. Reused structural timber is considered a promising alternative to conventional materials, such as concrete and steel, due to its potential to reduce embodied carbon emissions and temporarily store atmospheric carbon. However, the climate change impact of timber strongly depends on how biogenic carbon is modelled within life cycle assessment (LCA).

This thesis evaluates the climate change impact of reused structural timber using dynamic life cycle assessment (DynLCA). Five commonly used European wood species were assessed using several allocation methods and two biogenic carbon modelling approaches: the growth approach and the regrowth approach. Additional sensitivity analyses evaluated the influence of density, rotation period, reuse scenarios, and service life assumptions.

The results show that the choice of allocation method and biogenic carbon modelling approach is the dominant driver of the calculated climate change impact, with the same timber element capable of showing both strongly negative and positive impacts depending on the selected method. Growth-based approaches generally resulted in lower impacts due to immediate carbon crediting, while regrowth approaches produced more conservative results. Among the sensitivity parameters, service life and rotation period showed the strongest influence through their effect on the timing of carbon flows, while density resulted in more proportional changes and reuse processes contributed only a limited share to the total impacts.

Overall, the study demonstrates that dynamic LCA substantially alters the interpretation of reused timber systems compared to conventional static approaches, and that methodological choices regarding timing and allocation ultimately determine whether biogenic carbon functions as a climate benefit or burden.

Keywords

Dynamic life cycle assessment, reused structural timber, biogenic carbon, allocation methods, wood species

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I. INTRODUCTION

The construction sector is responsible for approximately 40% of global CO₂ emissions and remains one of the largest contributors to climate change [1]. While operational emissions of buildings

have decreased in recent years due to stricter energy regulations, the relative importance of embodied carbon emissions associated with construction materials has increased. As a result, growing attention is being given to circular construction strategies and the use of biobased materials [2].

Timber is increasingly considered a promising alternative to conventional construction materials, such as concrete and steel, due to its renewable origin and relatively low embodied emissions [1]. In addition, structural timber elements can often be reused after demolition, making timber particularly compatible with circular construction strategies and reducing the demand for new material production. Despite this potential, the reuse of structural timber remains limited in current construction practice [3].

An important characteristic of timber is the presence of biogenic carbon. During tree growth, atmospheric CO₂ is absorbed and stored within the wood material, where it can remain temporarily captured throughout one or multiple life cycles. As a result, timber has the potential to contribute to reducing climate change by delaying the release of atmospheric carbon. However, the inclusion of biogenic carbon within life cycle assessment (LCA) remains methodologically complex [4].

Current standards such as EN 15804 apply static carbon accounting approaches, where the timing of carbon uptake and release is not explicitly considered. Temporary carbon storage and delayed emissions are therefore represented in a simplified manner. Dynamic life cycle assessment (DynLCA) offers an alternative approach by accounting for the timing of emissions and removals over an assessed time horizon [5]. Additional challenges arise when timber elements are reused across multiple life cycles, as current standards provide only limited guidance regarding the allocation of biogenic carbon credits and burdens between consecutive life cycles. As a result, the choice of allocation method can

substantially influence the calculated climate change impact, yet no standardised approach currently exists [6].

II. METHODOLOGY

A. Goal and scope

This research evaluates the climate change impact of reused structural timber using a dynamic life cycle assessment (DynLCA) framework. The study focuses on reused structural timber beams within a European context and follows the modular structure of EN 15804+A2. The analysis is limited to the climate change indicator and considers both fossil and biogenic carbon flows over a 100-year assessment period.

The functional unit consists of 1 m³ of structural timber beam. Two consecutive life cycles are modelled in the baseline scenario, each with a service life of 50 years. The system boundaries include production processes (A1–A3), transport (A4), installation (A5), reuse processes, and end-of-life stages (C1–C4). In addition, several allocation methods are evaluated to assess how biogenic carbon credits and burdens are distributed between consecutive life cycles.

B. Wood species and biogenic carbon modelling

Five commonly used European wood species are included in the assessment: spruce (*Picea abies*), pine (*Pinus sylvestris*), larch (*Larix decidua*), oak (*Quercus robur*), and beech (*Fagus sylvatica*). Species-specific parameters including density, carbon fraction, and rotation period were collected from literature sources and existing databases.

Two different biogenic carbon modelling approaches are evaluated. The first approach applies immediate carbon uptake at the start of the assessment period (“growth approach”), while the second approach distributes carbon uptake over time according to forest regrowth (“regrowth approach”). Dynamic characterisation factors are subsequently used to account for the timing of emissions and removals throughout the assessed time horizon.

C. Allocation methods and reuse scenarios

Several allocation methods are assessed to analyse how biogenic carbon credits and burdens are distributed between consecutive life cycles. The study includes both growth-based allocation methods (G1–G5) and regrowth-based allocation methods (R1–R3).

In addition, four reuse scenarios are developed to analyse the environmental impact of different reuse processes. These scenarios differ in transport distances, storage conditions, and required processing steps. The scenarios range from direct

reuse with limited processing to more intensive reuse pathways including transport to material banks, surface treatments, and additional processing operations.

The life cycle inventory is modelled using SimaPro and primarily relies on background data from the Ecoinvent database. Additional process-specific information regarding reuse activities, transport assumptions, and auxiliary materials is collected from literature and practical observations.

D. Sensitivity analyses

Several sensitivity analyses are performed to assess the effect of density, rotation period, reuse scenario, and service life assumptions on the calculated climate change impacts. Particular attention is given to parameters influencing the timing of carbon uptake and release within the dynamic assessment framework.

The results are subsequently compared across wood species, allocation methods, and life cycle stages to evaluate the influence of temporal and methodological assumptions.

III. RESULTS

A. Growth allocation methods

Figure 1 shows the climate change impact of the assessed growth-based allocation methods (G1–G5) for spruce. Clear differences can be observed between the allocation approaches, despite all methods assessing the same timber element and system boundaries.

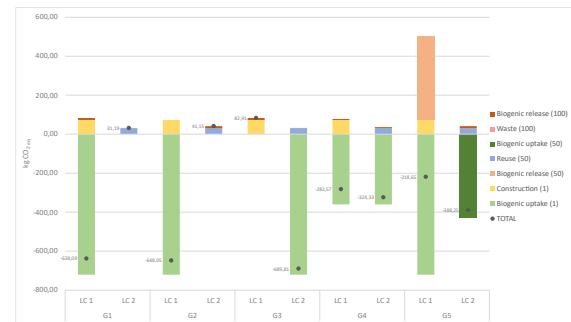


Figure 1 Climate change impact of growth-based allocation methods (G1–G5) for spruce

Method G1 allocates the full sequestration credit to the first life cycle, while the second life cycle only contains reuse and end-of-life processes. As a result, LC 1 shows strongly negative impacts, whereas LC 2 demonstrates positive impacts due to the absence of biogenic carbon uptake. Method G2 similarly allocates carbon uptake to the first life cycle, but transfers the release of biogenic carbon to the second

life cycle. This reduces the climate change impact of LC 1 compared to G1 while increasing the impact of LC 2.

Methods G4 and G5 distribute biogenic carbon flows more evenly between both life cycles. Method G4 shares both the biogenic carbon credits and burdens between the first and second life cycle, resulting in a more balanced distribution of impacts. In contrast, method G5 separates the two biogenic carbon cycles by assigning the uptake and release occurring within each cycle to the corresponding life cycle. Method G3 allocates the sequestration credit entirely to the second life cycle, strongly reducing the climate change impact of reused timber.

The results further show that the relative differences between allocation methods are considerably larger than the differences between wood species. Since carbon uptake is immediately credited at the start of the assessment period in the growth approach, the timing of sequestration remains identical for all species. As a result, variations between species are mainly governed by differences in density and carbon content, leading to relatively proportional changes in climate change impact.

B. Regrowth allocation methods

Figure 2 shows the climate change impact of the assessed regrowth-based allocation methods (R1–R3) for spruce. In contrast to the growth approach, carbon uptake is no longer credited immediately at the start of the assessment period, but distributed over time according to forest regrowth. As a result, the climate change impacts are consistently higher than for the corresponding growth-based allocation methods.

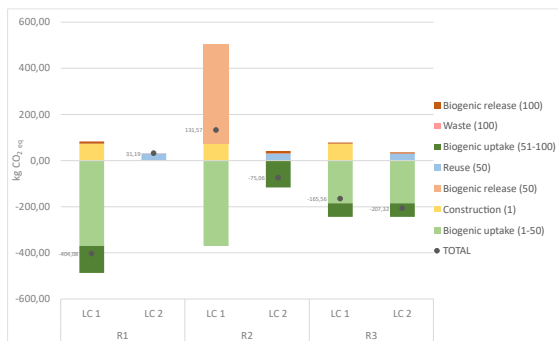


Figure 2 Climate change impact of regrowth-based allocation methods (R1–R3) for spruce

Method R1 allocates both biogenic carbon uptake and release to the first life cycle. Similar to G1, the

second life cycle therefore only contains reuse and end-of-life processes, resulting in positive impacts for LC 2. However, because carbon uptake is distributed over time, the sequestration credit is reduced compared to the growth approach, leading to higher impacts for LC 1 than in method G1.

Method R2 separates carbon uptake and release between both life cycles. Carbon uptake is assigned to the life cycle in which regrowth occurs, while biogenic carbon release is transferred to the subsequent life cycle. As a result, the climate change impact strongly depends on the timing of both sequestration and release. Compared to R1, this leads to higher impacts for LC 1 and more negative impacts for LC 2.

Method R3 follows a similar logic to G4 by distributing the benefits and burdens of biogenic carbon more evenly between both life cycles. Carbon uptake remains partially assigned to the second life cycle, while part of the release remains linked to the first life cycle. Consequently, the differences between LC 1 and LC 2 become less pronounced compared to methods R1 and R2.

In contrast to the growth approach, larger variations can also be observed between wood species. Since sequestration is distributed over time, species with longer rotation periods receive a smaller sequestration credit within the 100-year assessment period. This effect is particularly visible for hardwood species such as beech, where part of the carbon uptake occurs beyond the assessed time horizon.

C. Sensitivity analyses

The sensitivity analyses demonstrate that parameters affecting the timing of carbon flows have a strong influence on the calculated climate change impacts within the dynamic assessment framework. However, their influence depends strongly on the selected allocation method. This effect is particularly visible for allocation method R2, where biogenic carbon uptake is allocated to the life cycle in which sequestration occurs, while each life cycle bears a full independent release event. As a result, parameters influencing the timing of sequestration directly determine how much biogenic carbon credit is assigned to each life cycle.

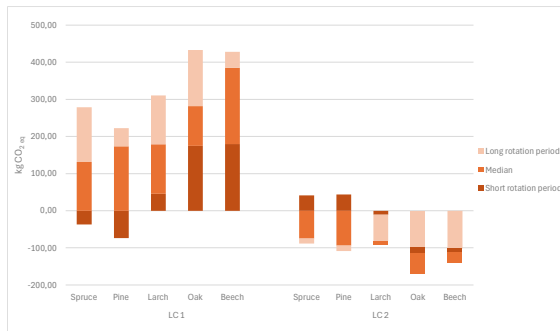


Figure 3 Influence of rotation period variation on allocation method R2

Figure 3 shows the influence of rotation period variation for allocation method R2. Clear differences can be observed between the minimum, median, and maximum rotation period scenarios. Longer rotation periods delay forest regrowth, causing a larger share of carbon uptake to occur during the second life cycle or beyond the assessed time horizon. Consequently, less sequestration credit is assigned to the first life cycle, resulting in substantially higher impacts. At the same time, a larger share of carbon uptake is shifted towards the second life cycle, resulting in more negative impacts for LC 2, provided the rotation period remains sufficiently short to avoid sequestration credits being lost outside the assessed time horizon. This effect is particularly visible for hardwood species such as oak and beech, where a substantial part of the carbon sequestration now occurs after the 100-year assessment period.

Compared to the allocation methods themselves, density shows a more proportional influence on the results. Species with higher densities generally result in larger fossil carbon emissions due to increased material mass, while simultaneously storing larger amounts of biogenic carbon. As a result, density affects both fossil and biogenic carbon flows, although its influence remains smaller than the temporal parameters related to carbon sequestration and release.

The influence of reuse processes remains relatively limited compared to the allocation of biogenic carbon flows. Transport distances, processing requirements, and auxiliary materials all affect the climate change impact of reuse scenarios. However, all assessed reuse scenarios still result in substantially lower impacts than the production of a new structural timber beam. The relative importance of reuse processes only becomes more pronounced for allocation methods where little to no biogenic carbon credit is assigned to the second life cycle.

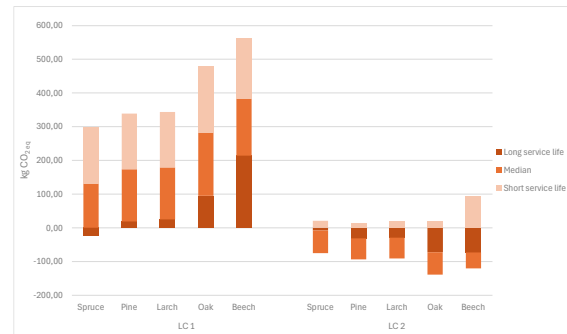


Figure 4 Influence of service life variation on allocation method R2

Figure 4 further shows the influence of service life variation for allocation method R2. Changing the service life affects both the timing of biogenic carbon release and the distribution of carbon uptake between life cycles. Shorter service lives shift carbon release to earlier points in time while simultaneously reducing the amount of sequestration occurring within the first life cycle. As a result, higher climate change impacts are observed. In contrast, longer service lives delay carbon release and increase the amount of carbon uptake assigned to the first life cycle, reducing the calculated impacts. Within the second life cycle, shorter service lives result in earlier carbon uptake, but this effect is offset by earlier carbon release. Longer service lives delay carbon release, but also reduce the amount of sequestration occurring within LC 2. As a result, the median service life scenario shows the lowest climate change impact for the second life cycle.

D. Discussion

The results show that the choice of allocation method and biogenic carbon modelling approach is the dominant driver of the calculated climate change impact, with growth-based methods consistently resulting in lower impacts due to immediate carbon crediting. The same timber element can show both strongly negative and positive climate change impacts depending on the selected method, demonstrating that methodological choices determine not only the magnitude but also the direction of the results.

The choice of allocation method also reflects a normative decision about the purpose of the assessment. Methods G1 and R1, and to an even greater extent G2, primarily promote the use of biobased materials by allocating the largest climate benefits to the first life cycle. Method G3 instead favours reuse by transferring sequestration credits to subsequent life cycles. Methods G4 and R3 attempt

to distribute benefits and burdens more equally between both life cycles, while G5 and R2 go further by treating each life cycle as independent, crediting each with its own uptake and holding each responsible for its own release.

The sensitivity analyses confirm that the influence of all assessed parameters depends strongly on the selected allocation method. Rotation period and service life show the strongest sensitivity through their effect on the timing of carbon flows. Density results in proportional changes to both fossil emissions and biogenic carbon storage, but its net effect on the climate change impact depends on whether uptake or release is allocated to the considered life cycle. Reuse processes contribute only a limited share to the total impact, though their relative importance increases when little biogenic carbon credit is assigned to the second life cycle.

Overall, the study demonstrates that dynamic LCA substantially alters the interpretation of reused timber systems compared to conventional static approaches. Whether biogenic carbon ultimately functions as a climate benefit or burden depends on the methodological choices made regarding timing and allocation.

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Dynamische Levenscyclusanalyse van Hergebruikt Constructiehout: De Invloed van Levenscyclusaannames en Houtsoorten

Killian Geenens

Promotor(en)/begeleider(s): prof dr. ir. arch. Marijke Steeman, ir. arch. Katrien Devos, David von Dufving

Abstract - De bouwsector is verantwoordelijk voor een aanzienlijk aandeel van de wereldwijde broeikasgasemissies, wat de interesse in circulaire en biobased bouwmaterialen vergroot. Hergebruikt constructiehout wordt beschouwd als een veelbelovend alternatief voor conventionele materialen zoals beton en staal vanwege het potentieel om embodied carbon-emissies te reduceren en atmosferische koolstof tijdelijk op te slaan. De klimaatimpact van hout hangt echter sterk af van de manier waarop biogene koolstof wordt gemodelleerd binnen levenscyclusanalyse (LCA).

Deze masterproef evalueert de klimaatimpact van hergebruikt constructiehout aan de hand van dynamische levenscyclusanalyse (DynLCA). Vijf veelgebruikte Europese houtsoorten werden onderzocht met behulp van verschillende allocatiemethoden en twee modelleringsbenaderingen voor biogene koolstof: de growth approach en de regrowth approach. Daarnaast omvat de studie sensitiviteitsanalyses met betrekking tot dichtheid, rotatieperiode, hergebruikscenario en aannames rond levensduur.

De resultaten tonen aan dat de keuze van allocatiemethode en modelleringsbenadering voor biogene koolstof de dominante bepalende factor is voor de berekende klimaatimpact. Hetzelfde houten element kan zowel sterk negatieve als positieve klimaatimpacts vertonen afhankelijk van de geselecteerde methode. Growth-based benaderingen resulteerden doorgaans in lagere impacts door de onmiddellijke toekenning van koolstofkredieten, terwijl regrowth-benaderingen meer conservatieve resultaten opleverden. Van de onderzochte sensitiviteitsparameters hadden levensduur en rotatieperiode de sterkste invloed via hun effect op het tijdstip van koolstofstromen, terwijl dichtheid meer proportionele veranderingen veroorzaakte en hergebruikprocessen slechts een beperkte bijdrage leverden aan de totale impacts.

Over het algemeen toont deze studie aan dat dynamische LCA de interpretatie van hergebruikte constructiehoutssystemen aanzienlijk verandert ten opzichte van conventionele statische benaderingen, en dat methodologische keuzes met betrekking tot timing en allocatie uiteindelijk bepalen of biogene koolstof fungeert als een klimaatvoordeel of -last.

Trefwoorden - Dynamische levenscyclusanalyse, hergebruikt constructiehout, biogene koolstof, allocatiemethoden, houtsoorten

I. INLEIDING

De bouwsector is verantwoordelijk voor ongeveer 40% van de wereldwijde CO₂-emissies en blijft één van de grootste bijdragers aan klimaatverandering [1]. Hoewel de operationele emissies van gebouwen de afgelopen jaren zijn afgenomen door strengere energieregelgeving, is het relatieve belang van embodied carbon-emissies verbonden aan bouwmaterialen toegenomen. Als gevolg hiervan gaat steeds meer aandacht naar circulaire bouwstrategieën en het gebruik van biobased materialen [2].

Hout wordt steeds vaker beschouwd als een veelbelovend alternatief voor conventionele bouwmaterialen zoals beton en staal vanwege zijn hernieuwbare oorsprong en relatief lage embodied emissies [1]. Bovendien kunnen structurele houten elementen vaak worden hergebruikt na ontmanteling, waardoor hout bijzonder compatibel is met circulaire bouwstrategieën en de vraag naar nieuwe materiaalproductie afneemt. Ondanks dit potentieel blijft het hergebruik van constructiehout beperkt binnen de huidige bouwpraktijk [3].

Een belangrijke eigenschap van hout is de aanwezigheid van biogene koolstof. Tijdens de groei van bomen wordt atmosferische CO₂ opgenomen en opgeslagen in het houtmateriaal, waar deze tijdelijk opgeslagen kan blijven gedurende één of meerdere levenscycli. Hierdoor heeft hout het potentieel om bij te dragen aan het beperken van klimaatverandering door de uitstoot van atmosferische koolstof uit te stellen. De opname van biogene koolstof binnen levenscyclusanalyse (LCA) blijft echter methodologisch complex [4].

Huidige standaarden zoals EN 15804 passen statische koolstofmodellering toe, waarbij de timing van koolstofopname en -uitstoot niet expliciet wordt meegenomen. Tijdelijke koolstofopslag en

uitgestelde emissies worden daardoor op een vereenvoudigde manier weergegeven. Dynamische levenscyclusanalyse (DynLCA) biedt een alternatieve benadering door rekening te houden met het tijdstip van CO₂-opnames en -emissies over een bepaalde tijdshorizon [5]. Bijkomende uitdagingen ontstaan wanneer houten elementen worden hergebruikt over meerdere levenscycli, aangezien huidige standaarden slechts beperkte richtlijnen bieden voor de allocatie van biogene koolstofkredieten en -lasten tussen opeenvolgende levenscycli. De keuze van allocatiemethode kan de berekende klimaatimpact bijgevolg aanzienlijk beïnvloeden, maar er bestaat momenteel geen gestandaardiseerde aanpak [6].

II. METHODOLOGIE

A. Doelstelling en scope

Dit onderzoek evalueert de klimaatimpact van hergebruikt constructiehout aan de hand van een dynamisch levenscyclusanalysekader (DynLCA). De studie focust op hergebruikte structurele houten balken binnen een Europese context en volgt de modulaire structuur van EN 15804+A2 [8]. De analyse beperkt zich tot de klimaatveranderingsindicator en houdt rekening met zowel fossiele als biogene koolstofstromen over een studieperiode van 100 jaar.

De functionele eenheid bestaat uit 1 m³ structurele houten balk. In het basisscenario worden twee opeenvolgende levenscycli gemodelleerd, elk met een levensduur van 50 jaar. De systeemgrenzen omvatten productieprocessen (A1–A3), transport (A4), installatie (A5), hergebruikprocessen en end-of-lifefases (C1–C4). Daarnaast worden verschillende allocatiemethoden geëvalueerd om te analyseren hoe biogene koolstofkredieten en -lasten verdeeld worden tussen opeenvolgende levenscycli.

B. Houtsoorten en modellering van biogene koolstof

Vijf veelgebruikte Europese houtsoorten zijn opgenomen in de analyse: spar (*Picea abies*), den (*Pinus sylvestris*), lariks (*Larix decidua*), eik (*Quercus robur*) en beuk (*Fagus sylvatica*). Soortspecifieke parameters waaronder densiteit, koolstoffractie en rotatieperiode werden verzameld uit literatuurbronnen en bestaande databanken.

Twee verschillende modelleringsbenaderingen voor biogene koolstof worden geëvalueerd. De eerste benadering kent onmiddellijke koolstofopname toe aan het begin van de studieperiode (“growth approach”), terwijl de tweede benadering de koolstofopname in de tijd

verdeelt volgens bosregeneratie (“regrowth approach”). Vervolgens worden dynamische karakterisatiefactoren gebruikt om rekening te houden met de timing van emissies en opnames gedurende de beoordelingsperiode.

C. Allocatiemethoden en hergebruikscenario's

Verschillende allocatiemethoden worden onderzocht om te analyseren hoe biogene koolstofkredieten en -lasten verdeeld worden tussen opeenvolgende levenscycli. De studie omvat zowel growth-based allocatiemethoden (G1–G5) als regrowth-based allocatiemethoden (R1–R3).

Daarnaast worden vier hergebruikscenario's ontwikkeld om de milieu-impact van verschillende hergebruikprocessen te analyseren. Deze scenario's verschillen in transportafstanden, opslagcondities en vereiste verwerkingsstappen. De scenario's variëren van direct hergebruik met beperkte verwerking tot intensievere hergebruiktrajecten met transport naar materialenbanken, oppervlaktebehandelingen en bijkomende verwerkingsoperaties.

De levenscyclusinventaris wordt gemodelleerd in SimaPro en maakt voornamelijk gebruik van achtergronddata uit de Ecoinvent-databank. Aanvullende proces-specifieke informatie met betrekking tot hergebruikactiviteiten, transportaannames en hulpmaterialen werd verzameld uit literatuur en observaties uit de praktijk.

D. Sensitiviteitsanalyses

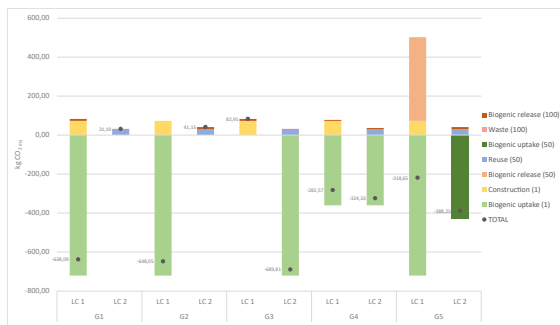
Verschillende sensitiviteitsanalyses worden uitgevoerd om het effect van densiteit, rotatieperiode, hergebruikscenario en aannames rond levensduur op de berekende klimaatimpacts te beoordelen. Bijzondere aandacht gaat naar parameters die de timing van koolstofopname en -uitstoot beïnvloeden binnen het dynamische beoordelingskader.

De resultaten worden vervolgens vergeleken over houtsoorten, allocatiemethoden en levenscyclusfasen om de invloed van temporele en methodologische aannames op hergebruikte constructiehoutsystemen te evalueren.

III. RESULTATEN

A. Growth-based allocatiemethoden

Figuur 1 toont de klimaatimpact van de onderzochte growth-based allocatiemethoden (G1–G5) voor spar. Ondanks dat alle methoden hetzelfde houten element en dezelfde systeemgrenzen beoordelen, kunnen duidelijke verschillen worden waargenomen tussen de allocatiebenaderingen.



Figuur 1 Klimaatimpact van growth-based allocatiemethoden (G1–G5) voor spar

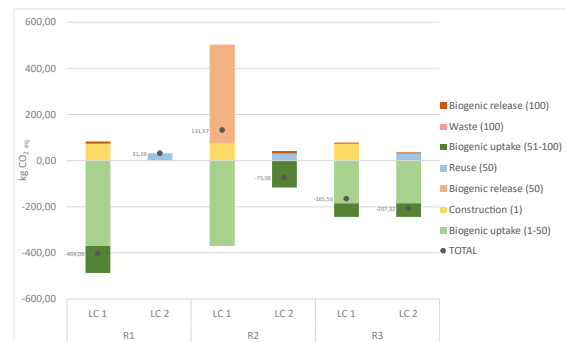
Methode G1 kent het volledige sequestratiekrediet toe aan de eerste levenscyclus, terwijl de tweede levenscyclus enkel hergebruik- en end-of-lifeprocessen bevat. Hierdoor vertoont LC 1 sterk negatieve impacts, terwijl LC 2 positieve impacts vertoont door de afwezigheid van biogene koolstofopname. Methode G2 kent op vergelijkbare wijze koolstofopname toe aan de eerste levenscyclus, maar verschuift de uitstoot van biogene koolstof naar de tweede levenscyclus. Hierdoor vermindert de klimaatimpact van LC 1 ten opzichte van G1, terwijl de impact van LC 2 toeneemt.

Methoden G4 en G5 verdelen biogene koolstofstromen gelijkmatiger tussen beide levenscycli. Methode G4 verdeelt zowel de biogene koolstofkredieten als -lasten tussen de eerste en tweede levenscyclus, wat resulteert in een meer gebalanceerde verdeling van de impacts. Methode G5 splitst daarentegen de twee biogene koolstofcycli door de opname en uitstoot binnen elke cyclus toe te wijzen aan de overeenkomstige levenscyclus. Methode G3 kent het sequestratiekrediet volledig toe aan de tweede levenscyclus, waardoor de klimaatimpact van hergebruikt hout sterk wordt verminderd.

De resultaten tonen verder aan dat de relatieve verschillen tussen allocatiemethoden aanzienlijk groter zijn dan de verschillen tussen houtsoorten. Aangezien koolstofopname in de growth approach onmiddellijk wordt toegekend aan het begin van de studieperiode, blijft het tijdstip van sequestratie identiek voor alle soorten. Variaties tussen houtsoorten worden daardoor voornamelijk bepaald door verschillen in densiteit en koolstofinhoud, wat leidt tot relatief proportionele veranderingen in klimaatimpact.

B. Regrowth-based allocatiemethoden

Figuur 2 toont de klimaatimpact van de onderzochte regrowth-based allocatiemethoden (R1–R3) voor spar. In tegenstelling tot de growth approach wordt koolstofopname niet langer onmiddellijk toegekend aan het begin van de beoordelingsperiode, maar verdeeld in de tijd volgens bosregeneratie. Hierdoor liggen de klimaatimpacts systematisch hoger dan bij de overeenkomstige growth-based allocatiemethoden.



Figuur 2 Klimaatimpact van regrowth-based allocatiemethoden (R1–R3) voor spar

Methode R1 kent zowel biogene koolstofopname als -uitstoot toe aan de eerste levenscyclus. Net zoals bij G1 bevat de tweede levenscyclus daardoor enkel hergebruik- en end-of-lifeprocessen, wat resulteert in positieve impacts voor LC 2. Omdat koolstofopname echter verdeeld wordt over de tijd, wordt het sequestratiekrediet kleiner dan bij de growth approach, wat leidt tot hogere impacts voor LC 1 dan bij methode G1.

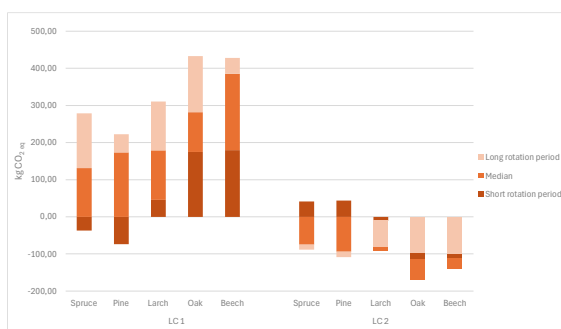
Methode R2 splitst koolstofopname en -uitstoot tussen beide levenscycli. Koolstofopname wordt toegewezen aan de levenscyclus waarin hergroei plaatsvindt, terwijl biogene koolstofuitstoot wordt doorgeschoven naar de daaropvolgende levenscyclus. Hierdoor hangt de berekende klimaatimpact sterk af van de timing van zowel sequestratie als uitstoot. In vergelijking met R1 leidt dit tot hogere impacts voor LC 1 en meer negatieve impacts voor LC 2.

Methode R3 volgt een gelijkaardige logica als G4 door de voordelen en lasten van biogene koolstof gelijkmatig te verdelen tussen beide levenscycli. Koolstofopname blijft gedeeltelijk toegewezen aan de tweede levenscyclus, terwijl een deel van de uitstoot gekoppeld blijft aan de eerste levenscyclus. Hierdoor worden de verschillen tussen LC 1 en LC 2 minder uitgesproken dan bij methoden R1 en R2.

In tegenstelling tot de growth approach kunnen ook grotere verschillen tussen houtsoorten worden waargenomen. Omdat sequestratie verdeeld wordt over de tijd, ontvangen soorten met langere rotatieperiodes een kleiner sequestratiekrediet binnen de beoordelingsperiode van 100 jaar. Dit effect is vooral zichtbaar bij hardhoutsoorten zoals beuk, waarbij een deel van de koolstofopname plaatsvindt buiten de beschouwde tijdshorizon.

C. Sensitiviteitsanalyses

De sensitiviteitsanalyses tonen aan dat parameters die de timing van koolstofstromen beïnvloeden een sterke invloed hebben op de berekende klimaatimpacts binnen het dynamische beoordelingskader. Hun invloed hangt echter sterk af van de geselecteerde allocatiemethode. Dit effect is bijzonder zichtbaar bij allocatiemethode R2, waarbij biogene koolstofopname wordt toegewezen aan de levenscyclus waarin sequestratie plaatsvindt, terwijl elke levenscyclus een volledige onafhankelijke uitstootgebeurtenis draagt. Parameters die de timing van sequestratie beïnvloeden bepalen daardoor rechtstreeks hoeveel biogeen koolstofkrediet aan elke levenscyclus wordt toegewezen.



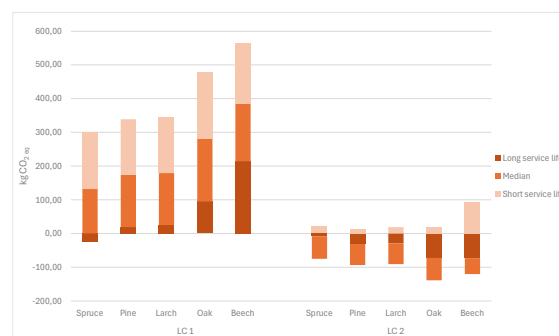
Figuur 3 Invloed van variatie in rotatieperiode op allocatiemethode R2

Figuur 3 toont de invloed van variatie in rotatieperiode voor allocatiemethode R2. Duidelijke verschillen kunnen worden waargenomen tussen de minimum-, mediaan- en maximumscenario's voor rotatieperiode. Langere rotatieperiodes vertragen boshergroei, waardoor een groter deel van de koolstofopname plaatsvindt tijdens de tweede levenscyclus of buiten de beschouwde tijdshorizon. Hierdoor wordt minder sequestratiekrediet toegewezen aan de eerste levenscyclus, wat resulteert in aanzienlijk hogere impacts. Tegelijkertijd verschuift een groter deel van de koolstofopname naar de tweede levenscyclus, wat resulteert in negatievere impacts voor LC 2, op voorwaarde dat de rotatieperiode voldoende kort

blijft zodat sequestratiekredieten niet buiten de beschouwde tijdshorizon vallen. Dit effect is vooral zichtbaar bij hardhoutsoorten zoals eik en beuk, waarbij een deel van de koolstofsequestratie plaatsvindt na de beoordelingsperiode van 100 jaar.

Densiteit veroorzaakt proportionele veranderingen in zowel fossiele emissies als biogene koolstofopslag, maar het netto-effect op de klimaatimpact hangt af van of opname dan wel uitstoot wordt toegewezen aan de beschouwde levenscyclus.

De invloed van de hergebruikprocessen zelf blijft relatief beperkt in vergelijking met de modellering en allocatie van biogene koolstofstromen. Transportafstanden, verwerkingsvereisten en hulpmaterialen beïnvloeden weliswaar de klimaatimpact van hergebruikscenario's. Alle onderzochte hergebruiktrajecten resulteren echter nog steeds in aanzienlijk lagere impacts dan de productie van een nieuwe structurele houten balk. Het relatieve belang van hergebruikprocessen wordt enkel groter bij allocatiemethoden waarbij weinig of geen biogeen koolstofkrediet wordt toegewezen aan de tweede levenscyclus.



Figuur 4 Invloed van variatie in levensduur op allocatiemethode R2

Figuur 4 toont verder de invloed van variatie in levensduur voor allocatiemethode R2. Het wijzigen van de levensduur beïnvloedt zowel het tijdstip van biogene koolstofuitstoot als de verdeling van koolstofopname tussen levenscycli. Kortere levensduren verschuiven koolstofuitstoot naar vroegere tijdstippen en verminderen tegelijkertijd de hoeveelheid sequestratie die plaatsvindt binnen de eerste levenscyclus. Hierdoor worden hogere klimaatimpacts waargenomen. Langere levensduren daarentegen vertragen koolstofuitstoot en verhogen de hoeveelheid koolstofopname die wordt toegewezen aan de eerste levenscyclus, waardoor de berekende impacts afnemen. Binnen de tweede levenscyclus leiden kortere levensduren tot eerdere

koolstofopname, maar dit effect wordt gecompenseerd door eerdere koolstofuitstoot. Langere levensduren vertragen koolstofuitstoot, maar verminderen ook de hoeveelheid sequestratie die plaatsvindt binnen LC 2. Hierdoor resulteert het mediaanscenario voor levensduur in de laagste klimaatimpact voor de tweede levenscyclus.

D. Discussie

De resultaten tonen aan dat de keuze van allocatiemethode en modelleringsbenadering voor biogene koolstof de dominante bepalende factor is voor de berekende klimaatimpact, waarbij growth-based methoden doorgaans lagere impacts opleveren door de onmiddellijke toekenning van koolstofkredieten. Hetzelfde houten element kan zowel sterk negatieve als positieve klimaatimpacts vertonen afhankelijk van de geselecteerde methode, wat aantoont dat methodologische keuzes niet alleen de omvang maar ook de richting van de resultaten bepalen.

De keuze van allocatiemethode weerspiegelt ook een normatieve beslissing over het doel van de beoordeling. Methoden G1 en R1, en in nog sterkere mate G2, bevorderen primair het gebruik van biobased materialen door de grootste klimaatvoordelen toe te kennen aan de eerste levenscyclus. Methode G3 bevordert daarentegen hergebruik door sequestratiekredieten over te dragen naar opeenvolgende levenscycli. Methoden G4 en R3 trachten voordelen en lasten gelijkmatiger te verdelen tussen beide levenscycli, terwijl G5 en R2 verder gaan door elke levenscyclus als onafhankelijk te beschouwen — elke cyclus krijgt zijn eigen opname gecrediteerd en draagt zijn eigen uitstoot.

De sensitiviteitsanalyses bevestigen dat de invloed van alle onderzochte parameters sterk afhangt van de geselecteerde allocatiemethode. Rotatieperiode en levensduur vertonen de sterkste gevoeligheid via hun effect op de timing van koolstofstromen. Densiteit veroorzaakt proportionele veranderingen in zowel fossiele emissies als biogene koolstofopslag, maar het netto-effect op de klimaatimpact hangt af van of opname dan wel uitstoot wordt toegewezen aan de beschouwde levenscyclus. Hergebruikprocessen leveren slechts een beperkte bijdrage aan de totale impact, hoewel hun relatieve belang toeneemt wanneer weinig biogeen koolstofkrediet wordt toegewezen aan de tweede levenscyclus.

Over het algemeen toont deze studie aan dat dynamische LCA de interpretatie van hergebruikte

constructiehoutsystemen aanzienlijk verandert ten opzichte van conventionele statische benaderingen. Of biogene koolstof uiteindelijk fungeert als een klimaatvoordeel of -last hangt af van de methodologische keuzes die worden gemaakt met betrekking tot timing en allocatie.

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Introduction

This thesis is structured into three parts, each addressing a specific aspect of the climate change impact of reused structural timber.

Part 1 consists of a literature review, in which the broader context of climate change, biobased construction materials, biogenic carbon, and life cycle assessment is discussed. In addition, existing approaches for modelling reuse and biogenic carbon within LCA are analysed to identify current challenges and research gaps.

Part 2 describes the methodology of the study. A dynamic life cycle assessment framework is developed to evaluate the climate change impact of reused structural timber. Five commonly used European wood species are assessed using different allocation methods and biogenic carbon modelling approaches. In addition, several sensitivity analyses are defined to evaluate the influence of density, rotation period, reuse scenario, and service life assumptions.

Part 3 presents and discusses the results of the dynamic LCA. First, the influence of the selected allocation methods and biogenic carbon modelling approaches is evaluated. Afterwards, different sensitivity analyses are discussed to assess how density, rotation period, reuse scenario, and service life assumptions influence the climate change impacts.

Finally, the thesis concludes with a general conclusion and discussion, in which the main findings, limitations, and future perspectives of the research are summarised.

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1. Context

Since the publication of the IPCC's Fifth Assessment Report in 2014, scientists have reached a broad consensus that human activities have significantly altered the Earth's atmospheric equilibrium and have been the dominant driver of global warming since the mid-20th century. Carbon dioxide is responsible for roughly 70% of human-induced greenhouse gas emissions. If current emission trends continue, atmospheric CO₂ levels are expected to double by the end of this century. Major contributors to these emissions include the burning of fossil fuels, widespread industrial pollution, deforestation, and the extensive use of energy-demanding materials such as steel, concrete, and plastics (Jeffree & de Munck, 2019).

At present, the building sector accounts for roughly 28% of global energy-related carbon dioxide (CO₂) emissions. When emissions associated with the production of construction materials are also considered, this proportion increases to approximately 40% (Kitek Kuzman et al., 2024). In addition, the sector is responsible for approximately 33% of total waste generation, 50% of global material flows, and around 33% of overall water consumption (Vlaanderen Circulair, 2024).

Reducing the environmental impact of the construction sector therefore requires both lowering fossil fuel dependence and improving the efficiency with which materials and resources are used (Jeffree & de Munck, 2019). Initiatives such as passive houses have significantly reduced a building's operational emissions during its usage phase. As a result, most of a building's total emissions—often between 50 and 70%—now stem from the earlier production stages rather than its use (Amiri et al., 2020). These production stages require substantial amounts of energy for the extraction, processing, and manufacturing of construction materials, commonly referred to as “embedded energy” (Kitek Kuzman et al., 2024).

Alongside reducing fossil energy consumption, the transition toward renewable and bio-based construction materials is increasingly regarded as another essential strategy. In this context, wood stands out as an environmentally responsible building material, as its ecological impact is considerably lower than that of many conventional man-made alternatives. Furthermore, wood can be recycled, recovered, and reused, enhancing its sustainability potential (Jeffree & de Munck, 2019).

However, reducing operational and material-related emissions alone is insufficient if construction materials continue to follow a predominantly linear life cycle. As a result, increasing attention is being directed toward circular economy principles within the construction sector. In a circular economy, the careful management of resources aims not only to reduce CO₂ emissions and environmental impact but also to generate economic and social value (Vlaanderen Circulair, 2024). Practically, this involves extending the life of buildings and materials through maintenance and renovation, reclaiming valuable components after demolition, and designing modular or easily disassembled construction systems (Poncelet et al., 2023). By keeping construction materials in circulation longer, the demand for fossil fuels and finite resources required for the production of new materials can be reduced, while emissions associated with waste processing are also avoided (Dougnet & Wagner, 2021).

Among the various circular strategies, reuse is considered one of the most effective approaches for reducing material demand and extending resource value within the construction sector. Reuse involves repurposing construction materials or components largely in their original form and

function, without transforming them into waste (Godina et al., 2025). In contrast to the traditional linear “take-make-dispose” model, reuse extends the service life of materials and reduces the need for newly manufactured alternatives. Consequently, reuse is increasingly promoted within European and regional circular construction policies (Vlaanderen Circulair, 2024).

Despite this potential, the construction industry has evolved and industrialized to such an extent that material reuse has largely been overlooked in modern practice (Kitek Kuzman et al., 2024). Even though many materials, including wood, could technically be reused after their first life cycle, current reuse rates in Northwestern Europe remain extremely low—around just 1% of all construction materials (FCRBE, 2021).

Consequently, reused timber represents a particularly promising strategy, combining the environmental advantages of bio-based materials with the principles of circular construction. Reusing wood offers a dual opportunity to reduce environmental impact and tackle climate-related challenges within the building sector, provided that these benefits can be assessed in a robust and consistent manner.

2. Biobased materials

2.1 Material characteristics

Wood possesses several material characteristics that make it particularly suitable for construction. It is comparatively lightweight and workable, allowing for easy handling, machining, and on-site adaptation. Because wooden structures often use dry joints rather than adhesives or wet connections, they can be dismantled with limited damage, supporting both design-for-disassembly approaches and future reuse. These qualities have contributed to wood's longstanding use as a versatile building material (Jeffree & de Munck, 2019).

Wood lends itself particularly well to the prefabrication of structural components, enabling a more efficient construction process. Prefabrication can reduce transport requirements by limiting the number of individual elements that need to be delivered to the site, while also significantly shortening on-site assembly time. Furthermore, the low self-weight of wooden structures can lead to reduced demands on foundations (Jeffree & de Munck, 2019).

In addition to being renewable, biobased materials such as timber often already result in lower climate change impacts than conventional construction materials such as steel and reinforced concrete. Research has shown that buildings constructed with engineered wood products often result in lower climate change impacts compared to functionally equivalent buildings constructed from steel or reinforced concrete (Kumar et al., 2024). These characteristics contribute to the growing relevance of timber as a low-impact construction material within more sustainable construction practices.

2.2 Market context

In addition to its favourable material characteristics, wood also plays a major economic and industrial role within the global construction sector. Within Europe, the wood-processing industry ranks as the fourth largest manufacturing sector in terms of the number of enterprises, making it economically and socially significant across the European Union (Jeffree & de Munck, 2019).

European softwood is derived from non-deciduous tree species such as spruce, pine, fir, and Douglas fir, with Germany, Sweden, Finland, Austria, and France being the main producers. While most of this timber is still sold within the European market, increasing quantities are exported to regions such as the Middle East, North Africa, and East Asia, where countries like China play an increasingly prominent role. Softwood is primarily used in the construction sector, but it is also widely applied in joinery, furniture, flooring, packaging, and industrial products (Jeffree & de Munck, 2019). Figure 1 illustrates the distribution of Europe's growing stock across the main tree species, highlighting the dominant role of softwood species within European forests (Korhonen & Stahl, 2020).

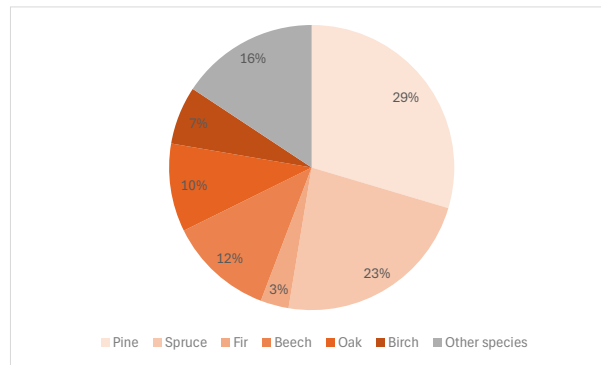


Figure 1. Europe's growing stock by main tree species (Korhonen & Stahl, 2020)

European hardwood, or sawn deciduous timber, comes from species such as oak, ash, beech, walnut, birch, and elm. The largest producing countries include Romania, Croatia, France, Germany, and Latvia. Hardwood is primarily marketed locally or nationally, though export outside the European Union—particularly to China, the Middle East, and North Africa—is becoming increasingly important. Hardwood is mostly used for interior applications such as furniture and flooring, but its naturally high durability also allows it to be applied untreated in a variety of construction uses (Jeffree & de Munck, 2019).

3. Reuse

3.1 Historical reuse practices

Although reuse is increasingly associated with contemporary circular construction strategies, the reuse of timber is not a recent practice. Historically, wood played a key role in the pre-industrial building economy, both as a primary construction material and for the fabrication of temporary and supportive structures such as cranes and scaffolding. Archaeological evidence shows that dismantling and reassembling entire wooden structures was already common practice before industrialized construction methods emerged (Rotor vzw, 2021).

Following the Industrial Revolution, however, the reuse of timber gradually declined, particularly in Northwestern Europe, where timber construction became less dominant and industrialized construction practices increasingly favoured linear production and demolition processes. In contrast, North America maintained a stronger tradition of timber construction and timber recovery practices (Bertino et al., 2021; Rotor vzw, 2021).

Much of the built environment in the United States was constructed using timber from old-growth forests that developed over centuries, resulting in wood with exceptional technical and aesthetic qualities as well as historical significance. While these structures were long demolished using heavy machinery, reducing valuable timber elements to rubble, growing awareness of the material's value has stimulated more careful dismantling practices aimed at preserving reusable timber components. Several companies and initiatives now specialize in the recovery and reuse of reclaimed timber from these structures (Solomon & Armster, 2019).

3.2 Concept of reuse

The term “reuse” is widely used in circular construction but is often interpreted inconsistently. In this study, reuse refers to the application of materials or components that retain their product status and are used again without undergoing significant transformation, typically for the same or a similar function. Importantly, reuse can also involve the application of materials in different contexts than originally intended, provided their core properties remain unchanged (Poncelet et al., 2023).

Reuse is distinct from recycling, which involves substantial physical or chemical transformation of materials into new raw inputs. Recycling typically reduces material value, limits application potential, and requires additional resources, placing it lower in the waste hierarchy, compared to reuse (Poncelet et al., 2023).

Within a circular construction approach, reuse aims to retain materials and components within the built environment for as long as possible, thereby reducing waste generation and the demand for newly produced materials (Godina et al., 2025). In the case of timber, extending the service life of wood products through reuse can additionally help reduce the pressure on forest resources and virgin timber production (Rotor vzw, 2021).

Despite its potential, the broader implementation of reuse within contemporary construction practices remains limited. A key challenge is the lack of standardized research methods, technical guidelines, and regulatory frameworks for reclaimed construction materials. In

addition, reuse often requires selective dismantling, storage, transport, inspection, and preparation processes that differ from conventional demolition and replacement practices. As a result, reuse is still not considered standard practice within the construction sector (Niu et al., 2021).

3.3 Reuse of structural timber

Wood is reused in a wide range of applications, including railway flooring, maritime timber, formwork panels, joinery, cladding, furniture, and interior finishing elements. Among these, structural timber is particularly relevant due to its extensive use within the construction sector (Poncelet et al., 2023; Rotor vzw, 2021). Consequently, this study focuses specifically on the reuse of structural timber elements.

Solid structural timber includes elements such as beams, columns, rafters, trusses, and floor joists. These elements are commonly produced from softwood species such as spruce, pine, Douglas fir, silver fir, and larch, selected for their favourable mechanical properties and workability. Hardwood species, particularly oak, are also encountered, especially in older structures. Depending on the age and origin of the material, reclaimed timber may possess technical, historical, and aesthetic value, often characterized by visible wear and weathered surfaces (Poncelet et al., 2023; Rotor vzw, 2021).

In addition to solid timber, engineered wood products such as glued laminated timber (glulam), cross-laminated timber (CLT), laminated veneer lumber (LVL), and Kerto are increasingly being considered for reuse. Glulam elements consist of timber lamellas that are finger-jointed and glued together with aligned grain directions, allowing for large spans and high structural performance. These elements are typically manufactured from softwood species such as spruce, pine, Douglas fir, and larch, with occasional use of hardwood species such as beech or oak (Jeffree & de Munck, 2019; Poncelet et al., 2023).

Although engineered wood products are increasingly considered for reuse, this study focuses specifically on solid structural timber beams, as these are significantly more available on the reuse market than products such as glulam (Rotor vzw, 2021).

3.4 Reclamation and preparation processes

Structural timber elements can often be recovered during demolition or dismantling works and subsequently reused in structural or non-structural applications. However, ensuring the structural reliability of reclaimed timber remains a key challenge, particularly when previous loading conditions, internal defects, or degradation processes are uncertain (Rotor vzw, 2021).

Timber reuse typically involves multiple reclamation and preparation steps before elements can be applied in a new construction context. Depending on the condition of the reclaimed timber and the intended reuse application, these processes may include selective dismantling, removal of metallic fasteners, cleaning, drying, repair, treatment, and resizing operations (Poncelet et al., 2023).

Initial reclamation operations often focus on the careful dismantling of timber structures to limit damage during removal. Mechanical fasteners such as nails, screws, bolts, and metal connectors may subsequently be removed manually or mechanically. Additional surface treatments can

include brushing, sanding, or planing in order to remove dirt, residues, or degraded surface layers. Depending on moisture conditions and biological degradation, drying and preservation treatments may also be required before reuse (Poncelet et al., 2023).

For structural timber specifically, additional assessment procedures are often necessary to evaluate the remaining mechanical performance of reclaimed elements. Existing defects such as cracks, deformations, holes, biological degradation, or damage caused by previous connections may influence the structural capacity of the timber and therefore require further inspection prior to structural applications (Poncelet et al., 2023).

4. Biogenic carbon

4.1 Carbon storage in biomass

In addition to its technical and circularity-related advantages, wood offers a distinctive climate-related characteristic. During growth, trees absorb carbon dioxide from the atmosphere through photosynthesis and convert it into biomass using solar energy, while oxygen is released back into the atmosphere. As a result, forests function as carbon sinks and wood acts as a reservoir for carbon (Jeffree & de Munck, 2019).

On average, one cubic metre of wood stores approximately 0.9 tonnes of CO₂ (Jeffree & de Munck, 2019). When trees are harvested and processed into marketable wood products, this stored carbon remains locked within the material in the form of biogenic carbon (CE Delft, 2021; SGS Search, 2022).

4.2 Carbon debt and forest regrowth

Harvesting biomass for material use reduces the amount of carbon stored within the forest ecosystem, creating a temporary carbon deficit referred to as carbon debt. Because the harvested biomass is no longer present in the forest, it can no longer continue absorbing atmospheric CO₂, resulting in a temporary increase in atmospheric carbon concentrations (Strengers et al., 2024).

Over time, this carbon debt may gradually decrease through forest regrowth. As new biomass develops, carbon is reabsorbed from the atmosphere and stored again within the growing forest. The recovery of the original carbon stock depends on continued forest regeneration and sustainable forest management practices, which are commonly supported through certification schemes such as FSC or PEFC (SGS Search, 2022).

4.3 Rotation period

The time required for forest biomass to fully regenerate is defined as the rotation period. By the end of this period, the regrown biomass has reabsorbed an amount of CO₂ equivalent to that which was originally removed through harvesting (Pittau et al., 2017).

When wood products store carbon over extended periods, atmospheric carbon remains stored within the material while forest regrowth simultaneously continues to absorb CO₂. This creates a temporary cumulative carbon storage effect (CE Delft, 2021).

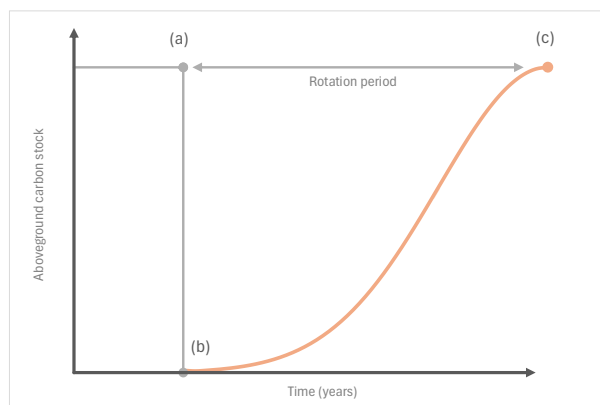


Figure 2. Simplified representation of a carbon-flux-neutral system (Cherubini et al., 2011)

Figure 2 illustrates a simplified carbon-flux-neutral system, consisting of three stages: (a) a steady-state biomass system, (b) harvesting combined with regrowth, and (c) full recovery of the original carbon stock after one rotation period (Cherubini et al., 2011).

The duration of the rotation period varies depending on tree species and forest management practices, directly influencing the timing of carbon uptake and recovery. As a result, rotation periods play an important role in determining the temporal climate impact of wood-based materials.

4.4 Species-dependent parameters

The amount and timing of biogenic carbon storage are influenced by several species-dependent parameters, including wood density, carbon fraction, and rotation period. Variations in these parameters can substantially affect both the quantity of carbon stored within timber products and the temporal distribution of carbon uptake and release (Horan et al., 2025).

The carbon content of wood is commonly approximated as 50% of dry biomass, although reported carbon fractions may vary between wood species and literature sources, making species-specific values more appropriate for detailed comparative assessments (Horan et al., 2025). Similarly, wood density differs considerably across species and geographical contexts. Softwood species generally show lower densities than hardwood species, resulting in lower amounts of stored biogenic carbon per cubic metre of timber. Reported dry wood densities for European conifer species typically range between approximately 0.35 and 0.57 t/m³, while hardwood species generally exhibit substantially higher densities (Horan et al., 2025).

In addition to the quantity of stored carbon, forest growth characteristics also influence the temporal behaviour of biogenic carbon flows. Rotation periods may vary substantially between species and forestry practices, affecting the timing of forest regrowth and carbon sequestration following harvest. Pittau et al. (2017) further highlight that parameters related to biomass growth and carbon storage can significantly influence the climate change impact of wood products (Pittau et al., 2017).

4.5 Delayed emissions

At the end of their service life, wood products release the stored biogenic carbon back into the atmosphere through processes such as combustion, decomposition, or methane digestion (Strengers et al., 2024). While CO₂ is the primary emission, other greenhouse gases such as methane (CH₄), carbon monoxide (CO), and nitrous oxide (N₂O) may also be emitted (Brandão et al., 2013; Levasseur et al., 2013).

A key characteristic of biogenic carbon is that carbon uptake and carbon release occur at different moments in time. Carbon is first removed from the atmosphere during biomass growth and only released again after the service life of the wood product. This creates delayed emissions, where carbon remains temporarily stored within the material before returning to the atmosphere (CE Delft, 2021).

The longer carbon remains stored in wood products, the longer atmospheric CO₂ concentrations remain temporarily reduced (CE Delft, 2021; SGS Search, 2022). This delay can contribute to climate change mitigation by postponing greenhouse emissions and reducing radiative forcing during the storage period. This effect is more pronounced in wooden structures with long service lives (Levasseur et al., 2012; Strengers et al., 2024). Consequently, extending the lifespan of wood products and keeping timber in circulation for longer periods can increase the duration of carbon storage and postpone the release of biogenic carbon (Douguet & Wagner, 2021).

Nevertheless, the climate benefits associated with temporary carbon storage remain subject to debate. When assessed over an infinite time horizon, delayed emissions do not permanently avoid atmospheric carbon release but instead postpone emissions to a later moment in time (Brandão et al., 2013; Levasseur et al., 2013).

Consequently, accurately evaluating the climate impact of wood-based materials requires assessment methods capable of representing the temporal dynamics of biogenic carbon flows.

5. Biogenic carbon modelling in LCA

5.1 Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a standardized method used to evaluate the environmental impacts associated with a product, material, building element, or entire building throughout its life cycle. By quantifying resource inputs and emissions across all stages—from raw material extraction to end-of-life treatment—LCA provides a transparent basis for comparing materials and identifying where the greatest environmental burdens occur (OVAM, 2023).

Its relevance in the construction sector has grown significantly, particularly as operational energy use decreases and material-related impacts become more dominant. In low-energy buildings, material production can account for up to half of the total environmental impact, making a life cycle perspective essential (Ghyoot et al., 2021).

In Flanders and across Europe, LCA is considered a crucial tool for supporting sustainable construction and broader circular economy goals. Adopting a full life cycle perspective helps avoid burden shifting between phases and enables designers and policymakers to make well-informed, evidence-based decisions (OVAM, 2023).

LCA follows four interconnected phases: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation. This framework enables the assessment of a wide range of environmental impacts, including climate change, eutrophication, acidification, human toxicity, particulate matter formation, and resource depletion (Delem et al., 2021).

5.2 Life cycle stages in construction

In the European construction context, LCAs are structured according to the modular framework defined in EN 15804 and EN 15978 (Dougnet & Wagner, 2021). This framework divides the life cycle into four main stages.

Module A includes extraction and processing of raw materials, manufacturing (A1–A3), transport to site (A4), and installation (A5). Many construction materials show their highest embodied impacts in this early stage (Dougnet & Wagner, 2021).

The use stage (B1–B7) covers maintenance, repair, replacement, and refurbishment. Assumptions about service life and replacement intervals strongly influence total life-cycle impacts (Dougnet & Wagner, 2021).

Module C includes deconstruction (C1), transport (C2), processing (C3), and disposal (C4). End-of-life choices influence both direct impacts and the potential for material recovery (Dougnet & Wagner, 2021).

Module D reports potential benefits beyond the assessed system, such as reuse, recycling, or energy recovery. Correctly accounting for these benefits is essential for representing the environmental advantages of circular construction strategies (Dougnet & Wagner, 2021).

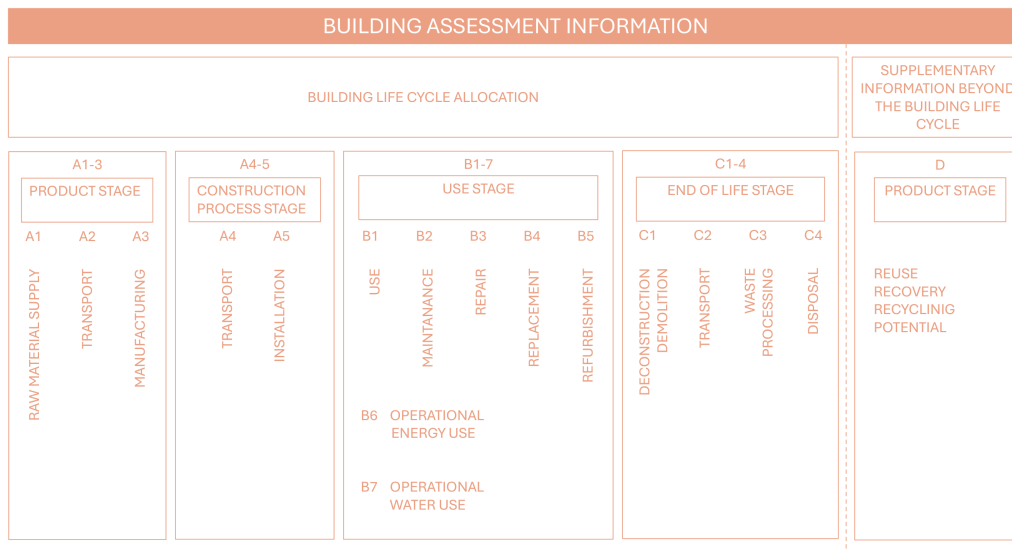


Figure 3. Overview of the life cycle stages and system boundaries within the European standard EN 15978:2011 (CEN 2011a) (OVAM, 2013)

This modular structure provides a standardized way to track environmental impacts across the life cycle of construction materials. However, conventional LCA is primarily designed for linear product systems and single life cycles. Although Module D aims to account for potential benefits beyond the assessed system boundary, such as reuse and recycling, methodological guidance regarding the allocation of these future benefits remains limited. These challenges are particularly relevant for biobased materials such as timber, where carbon storage and reuse may extend across multiple life cycles (Dougnet & Wagner, 2021).

5.3 LCA in practice: The Belgian context (TOTEM)

In Belgium, Life Cycle Assessment (LCA) is commonly applied through TOTEM (Tool to Optimise the Total Environmental impact of Materials), developed based on the MMG (Milieugerelateerde Materiaalimpact van Gebouw(element)en) methodology. TOTEM follows European LCA standards such as EN 15804 and is aligned with the Product Environmental Footprint (PEF) framework (OVAM, 2023).

The tool functions as a decision-support instrument for architects, engineers, and policymakers, enabling the environmental evaluation of building materials and components. It relies on a combination of generic datasets from databases such as Ecoinvent and product-specific Environmental Product Declarations (EPDs), allowing assessments to be performed at both element and building scale (OVAM, 2023).

A key feature of TOTEM is its multi-indicator approach. Environmental impacts are evaluated across a broad set of impact categories, grouped into several families, covering aspects such as resource depletion, toxicity, ecosystem impacts and climate change. To facilitate comparison between design options, these indicators are aggregated into a single weighted environmental score, typically expressed at building level (OVAM, 2023).

While this comprehensive approach allows for a broad environmental evaluation, climate change—expressed in CO₂-equivalents—remains one of the most influential indicators, particularly in the context of bio-based materials (OVAM, 2023).

Despite its relevance for practice, the current implementation of TOTEM presents several limitations when applied to circular construction strategies involving multiple life cycles. The tool assumes a fixed service life of 60 years, offers limited flexibility in transport modelling, and does not yet fully integrate Module D for reuse scenarios (Ghyoot et al., 2021).

5.4 Global warming potential and climate change indicators

As discussed in section 5.1, LCA evaluates a wide range of environmental impact categories. Among these, climate change is one of the most important and widely applied indicators within construction-related LCA studies. Climate change impacts are assessed based on the emission behaviour of greenhouse gases and their influence on atmospheric warming. To quantify these effects, greenhouse gas emissions are commonly expressed using climate indicators such as Global Warming Potential (GWP) (Brandão et al., 2013).

5.4.1 Greenhouse gas behaviour and atmospheric processes

Greenhouse gases (GHG's) contribute to climate warming by trapping heat within the Earth's atmosphere. They absorb part of the energy radiated from the Earth's surface and slow down its release into space, creating an insulating effect. Different greenhouse gases, such as carbon dioxide (CO₂) and methane (CH₄), vary considerably in both their capacity to absorb energy and the length of time they remain active in the atmosphere (EPA, 2025).

Following a pulse emission of CO₂, atmospheric concentrations do not decrease at a constant rate. Instead, CO₂ is gradually removed from the atmosphere through uptake by natural sinks, including forests, oceans, and soils. This time-dependent behaviour is typically represented by a decay curve, or an impulse response function. A commonly applied model is the Bern carbon cycle model, which describes how emitted CO₂ decays over time (Pittau et al., 2017). Figure 4 illustrates this atmospheric decay behaviour for a pulse CO₂ emission over time, showing that part of the emitted CO₂ remains in the atmosphere for several centuries (Cherubini et al., 2011).

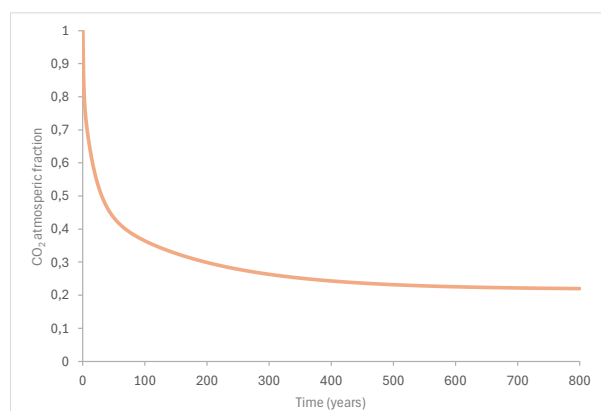


Figure 4. Atmospheric decay of a pulse CO₂ emission (Cherubini et al., 2011)

5.4.2 Global warming potential (GWP)

To compare greenhouse gases with different atmospheric behaviours, the Intergovernmental Panel on Climate Change (IPCC) developed the Global Warming Potential (GWP) indicator. GWP expresses the cumulative radiative forcing caused by the emission of one tonne of a specific greenhouse gas over a defined period, relative to the impact of emitting one tonne of CO₂ (EPA, 2025).

GWP is derived from the concept of radiative forcing, which describes changes in the Earth's energy balance caused by atmospheric disturbances, including greenhouse gas emissions (ARUP, 2024; Cherubini et al., 2011).

Table 1. GWP values for Time Horizons, as published by IPCC in the Fourth Assessment Report (Cherubini et al., 2011)

Time Horizon	20 years	100 years	500 years
CO ₂	1	1	1
CH ₄	72	25	7,6
N ₂ O	289	298	153

A key parameter in GWP calculations is the selected time horizon (TH). Although the 100-year time horizon (GWP100) is most widely used in policy and research, its suitability remains subject to debate (Brandão et al., 2013). The IPCC therefore also provides GWP values for shorter and longer time horizons, such as 20 and 500 years. Table 1 presents the corresponding GWP values for selected greenhouse gases across these different time horizons. Shorter time horizons emphasize short-lived climate forcers such as methane, while longer time horizons reduce the relative importance of near-term emissions (Cherubini et al., 2011).

5.4.3 Use of GWP in LCA

In conventional LCA, greenhouse gas emissions are converted into CO₂-equivalents using fixed characterization factors, usually based on GWP100. Emissions are aggregated over the life cycle without explicitly considering when they occur (EPA, 2025).

As discussed in Chapter 4, biogenic carbon is characterized by a temporal separation between uptake and release. However, this temporal dimension is not reflected in the use of fixed GWP characterization factors. Emissions occurring at different moments in time are therefore treated as equivalent, even though their actual influence on atmospheric CO₂ concentrations differs (Levasseur et al., 2010).

This simplification supports consistency and comparability across LCA studies, but it also introduces an important limitation: The duration of carbon storage does not influence the climate impact. This is particularly relevant for bio-based materials and reuse scenarios involving extended service lives (Levasseur et al., 2010).

5.4.4 Limitations of GWP100

Applying a fixed GWP100 characterization factor across an entire life cycle introduces conceptual inconsistencies when emissions occur late in time. Emissions released near the end of the study period are assigned their full GWP100 impact, even though they influence the atmosphere for less than 100 years within the assessment window (Levasseur et al., 2010).

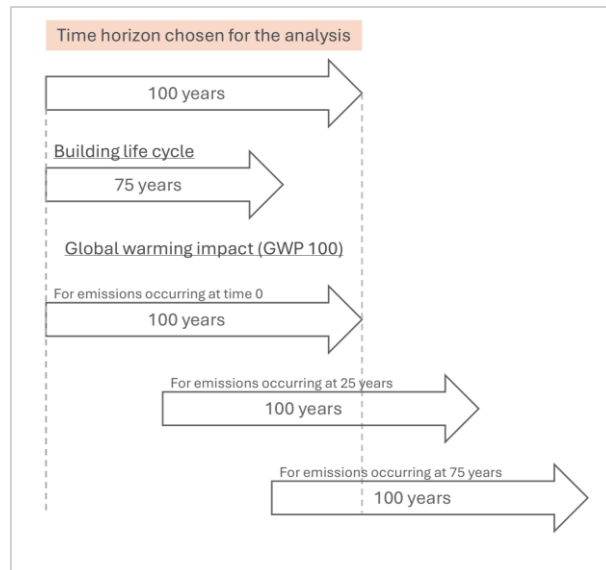


Figure 5. Illustration of the inconsistency in time frames for global warming LCIA with the example of a 75-year lifetime building (Levasseur et al., 2010)

For example, if a building reaches its end of life after 75 years, assigning a full GWP100 value to these emissions effectively extends the assessment period beyond the original time horizon. This means that delaying emissions does not reduce their calculated climate impact within conventional GWP-based LCAs (Levasseur et al., 2010).

5.5 Static approaches

Most current LCA standards and tools model biogenic carbon using static approaches based on fixed GWP characterization factors. Within these approaches, carbon uptake and release are treated as climatically equivalent regardless of when they occur. Carbon uptake during biomass growth is therefore assumed to be balanced by carbon release at the end of life of the wood product (Peñaloza et al., 2016; Pittau et al., 2017).

5.5.1 0/0 approach

The simplest representation of this assumption is the 0/0 approach, in which biogenic carbon uptake and release are not explicitly modelled. As a result, no biogenic carbon flows are assigned to any life cycle module, and the overall climate impact is assumed to be zero (Hoxha et al., 2020).

- Module A (production): 0
- Module C (end of life): 0
- Total life cycle impact: 0

This approach is currently applied within the Product Environmental Footprint (PEF) methodology (Hoxha et al., 2020).

5.5.2 -1/+1 approach

A more detailed static method is the -1/+1 approach, which explicitly tracks carbon flows while maintaining overall neutrality. Carbon uptake is accounted for as a negative emission during production (Module A), while an equivalent release is assigned to the end-of-life phase (Module C) (Hoxha et al., 2020).

- Module A (production): -1
- Module C (end of life): +1
- Total life cycle impact: 0

Although this approach allows basic tracking of biogenic carbon flows, the total climate impact remains zero regardless of storage duration or the number of life cycles through which the material passes.

This approach is prescribed in standards such as EN 15804 and EN 15978 and serves as a starting point for several simplified dynamic assessment methods (Hoxha et al., 2020).

5.5.3 Limitations of static approaches

Static approaches are widely used due to their simplicity and compatibility with existing standards. However, they overlook several key characteristics of biogenic carbon (Hoxha et al., 2020).

Firstly, they do not account for the timing of emissions and removals. Carbon uptake and carbon release are treated as equivalent regardless of when they occur, meaning that the duration of carbon storage has no influence on the calculated results (Hoxha et al., 2020).

Secondly, static approaches do not account for forest rotation periods, implicitly assuming that forest regrowth is complete by the time the product reaches its end of life. This neglects differences between biomass types with varying regeneration cycles (Hoxha et al., 2020).

Thirdly, static approaches do not differentiate between end-of-life scenarios. Reuse and recycling can significantly extend carbon storage duration, yet assigning biogenic carbon release directly to Module C regardless of subsequent reuse does not reflect the actual behaviour of carbon in circular systems (Hoxha et al., 2020).

Addressing these limitations requires modelling approaches that explicitly account for time-dependent carbon flows (Hoxha et al., 2020).

5.6 Dynamic approaches

To address the limitations of fixed characterization factors, several approaches have been developed that incorporate the timing of greenhouse gas emissions into climate impact assessment (Levasseur et al., 2010). The most physically consistent methods use dynamic characterization factors, which evaluate emissions differently depending on when they occur. This allows climate impacts to better reflect actual atmospheric behaviour over time (Levasseur et al., 2010).

Dynamic carbon modelling requires the definition of three time-related parameters:

- Time horizon: the period over which climate impacts are evaluated.
- Study period: the lifespan of the assessed product or building.
- Rotation period: the time required for biomass to fully regenerate.

These parameters play a central role in the modelling approaches discussed in the following sections.

5.6.1 Simplified dynamic approaches

Simplified dynamic approaches aim to account for the climate relevance of delayed emissions without modelling emissions and removals explicitly over time. These methods are commonly referred to as ton-year approaches and are based on the principle that storing carbon temporarily provides a climate benefit that can be expressed as a credit in kg CO₂-equivalents (Levasseur & Brandão, 2011).

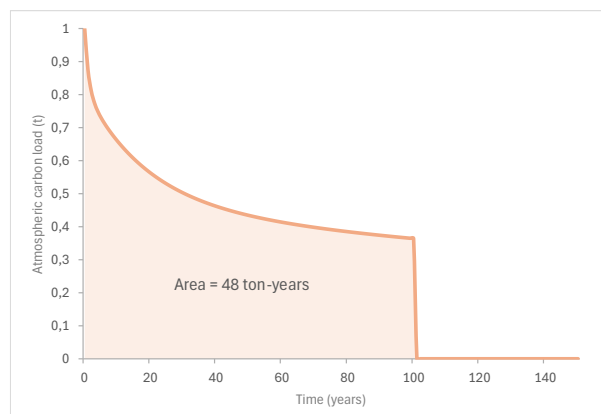


Figure 6. The cumulative radiative forcing of 1 t CO₂, considering a 100 year TH (Levasseur et al., 2012)

Figure 6 illustrates the ton-year concept based on the cumulative radiative forcing of a 1 t CO₂ pulse emission over a 100-year time horizon. The shaded area under the atmospheric decay curve corresponds to approximately 48 ton-years and forms the basis for simplified dynamic assessment methods (Levasseur et al., 2012). Several ton-year methods have been proposed in the literature, each applying different assumptions to quantify this storage benefit.

Lashof method

The Lashof method treats temporary carbon storage as a shift in the timing of emissions. Instead of assigning the climate impact at the moment of release, the emission is effectively moved forward in time. The resulting benefit corresponds to the portion of the emission impact that falls outside the standard 100-year assessment period. Carbon storage is therefore credited when it delays emissions beyond the GWP100 time horizon (Levasseur et al., 2012).

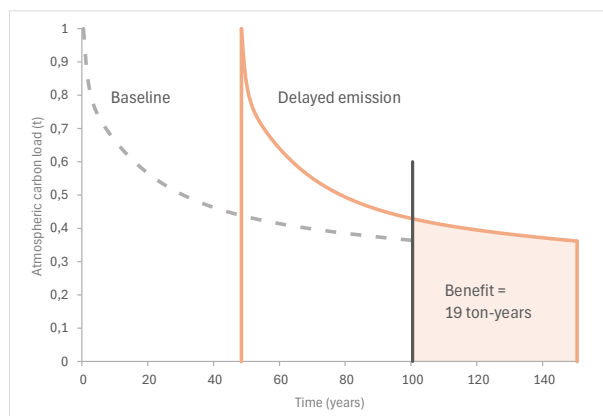


Figure 7. The Lashof method, based on the cumulative radiative forcing of 1 t CO₂ (Levasseur et al. 2012)

Figure 7 illustrates this principle by comparing the cumulative radiative forcing of an immediate and delayed CO₂ emission. The shaded area represents the avoided radiative forcing within the 100-year assessment period and corresponds to the climate benefit associated with temporary carbon storage.

ILCD Handbook method

The ILCD approach also provides a simplified calculation of delayed emission benefits. Each emission, expressed in kg CO₂-equivalents using conventional GWP values, is multiplied by the duration of storage. A fixed weighting factor of -0.01 is then applied to calculate the corresponding credit. Emissions occurring after the 100-year time horizon are reported separately (Brandão et al., 2013).

PAS2050 method

The PAS 2050 method distinguishes between short-term and long-term storage effects. Emissions occurring within the first 25 years are treated using a linear approximation of the Lashof method. Emissions delayed beyond 25 years, and up to 100 years, are assessed using the same weighting factor as in the ILCD approach. For construction materials with long service lives, this latter category is particularly relevant (DEFRA et al., 2011).

Comparison and limitations

Simplified dynamic approaches are relatively easy to apply and allow timing effects to be incorporated into LCA without requiring fully dynamic inventories. However, these methods rely on simplified weighting factors and generalized assumptions regarding carbon storage and delayed emissions.

Figure 8 compares the weighting factors used in the ILCD/PAS2050 and Lashof methods for delayed emissions over a 100-year time horizon. Although some differences exist between the methods, both approaches show relatively similar weighting trends over time.

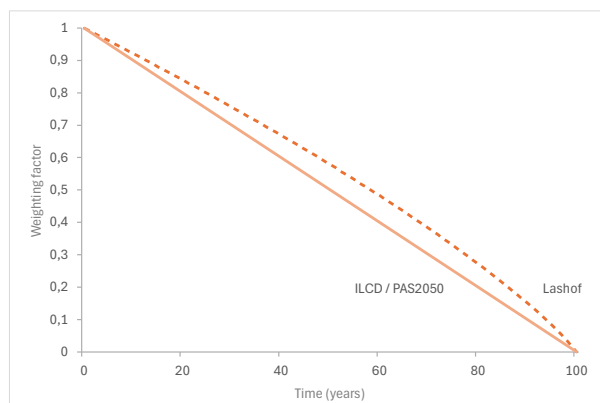


Figure 8. Comparison of 100-year weighting factors for delayed emission (Arup, 2024)

These methods are nevertheless often criticized for potentially overstating the climate benefits of temporary carbon storage. Results remain highly sensitive to assumptions regarding storage duration and time horizon and should therefore be interpreted cautiously, particularly when comparing scenarios involving different service lives or reuse strategies (Levasseur & Brandão, 2011).

5.6.2 Fully dynamic approaches

Fully dynamic approaches explicitly model greenhouse gas emissions and removals as functions of time. Emissions and sequestration are evaluated on a time-resolved basis, typically year by year, using time-dependent characterization factors (Levasseur et al., 2013).

A key implication of this approach is that the timing of carbon sequestration in biomass must be explicitly defined. While this aspect is implicitly treated in static and simplified approaches, fully dynamic modelling requires a clear assumption regarding when carbon uptake occurs within the system boundary. Two main carbon sequestration scenarios are commonly distinguished (Hoxha et al., 2020):

- In the growth scenario, carbon sequestration is assumed to have occurred entirely before the product enters the life cycle. Trees are considered fully grown at the time of harvest, and carbon uptake is therefore assigned to the production phase (Module A1) (Hoxha et al., 2020).
- In the regrowth scenario, carbon sequestration occurs after harvest. Forest regrowth is assumed to begin immediately following biomass removal, and carbon uptake is accounted for during the use phase of the product (Module B1) (Hoxha et al., 2020).

These assumptions result in fundamentally different carbon flux trajectories. In the growth scenario, carbon uptake precedes carbon release, ensuring carbon neutrality within the model. In contrast, under the regrowth scenario, emissions may occur before full sequestration is achieved, leading to a temporary increase in atmospheric CO₂ concentrations (Hoxha et al., 2020).

The regrowth scenario is generally considered more conservative and more consistent with sustainable forest management principles, as it explicitly requires harvested biomass to be regenerated (Hoxha et al., 2020).

Because sequestration occurs progressively over time, fully dynamic approaches can also capture differences between biomass types with varying rotation periods, making them particularly relevant for assessing wood species with different growth characteristics (Hoxha et al., 2020).

DynLCA (Levasseur et al.)

Dynamic Life Cycle Assessment (DynLCA) was developed to align the time frame of life cycle inventories with the time horizon used in climate impact assessment (Levasseur et al., 2010). The approach integrates a dynamic inventory, which tracks emissions and removals over time, with a dynamic impact assessment, where emissions occurring later in time are evaluated over a shorter remaining time horizon (Levasseur et al., 2013).

As a result, DynLCA reflects the decreasing climate relevance of emissions that occur further in the future, providing a more physically consistent representation of atmospheric processes (Levasseur et al., 2010).

GWPbio (Cherubini et al.; Guest et al.)

The GWPbio approach introduces time-dependent characterization factors specifically for biogenic CO₂ emissions. Unlike DynLCA, it does not require a dynamic life cycle inventory. Instead, temporal effects are embedded within the characterization factors themselves.

Originally developed for bioenergy systems, the method was later extended to include temporary carbon storage in biobased products. It accounts for both the rotation period of biomass and the duration of carbon storage in the product (Cherubini et al., 2011; Guest et al., 2013).

The approach combines:

- the atmospheric decay of CO₂ (impulse response function)
- an emission function
- a biomass growth curve

As a result, GWPbio implicitly follows a regrowth-type assumption for carbon sequestration.

GWPbio factors are applied similarly to conventional GWP values by multiplying them with biogenic CO₂ emissions to express climate impacts in CO₂-equivalents (Cherubini et al., 2011; Guest et al., 2013).

Strengths and limitations

Compared to DynLCA, GWPbio is easier to implement, as it avoids the need for a time-explicit inventory. However, it also introduces limitations (Breton et al., 2018). Biogenic emissions are treated using dynamic characterization factors, while fossil emissions are still assessed using fixed GWP values. This creates a combination of static and dynamic elements within a single indicator framework, which may affect the consistency of results (Breton et al., 2018).

More broadly, DynLCA provides the most detailed and physically consistent representation of time-dependent carbon processes. They are particularly relevant for assessing long-lived wood products and reuse scenarios. At the same time, results remain highly sensitive to modelling assumptions, including time horizon, rotation period, and sequestration scenario.

5.6.3 Synthesis

Across all modelling approaches, the treatment of time plays a critical role in determining the calculated climate impact of biogenic carbon. Static approaches rely on fixed characterization factors and therefore treat emissions occurring at different moments as equivalent, while dynamic approaches explicitly incorporate temporal effects into climate impact assessment.

Simplified dynamic methods introduce timing effects through approximations, whereas fully dynamic approaches explicitly model emissions and removals over time using time-dependent characterization factors.

Consequently, the selection of a modelling framework strongly influences how differences between materials, life cycle assumptions, wood species, and reuse scenarios are represented within LCA studies involving bio-based materials.

Table 2. Comparison of biogenic carbon models (Van Gulck et al., 2025)

Approach	Static		Simplified dynamic	Dynamic	
	0/0	-1/1	Lashof, ILCD, PAS 2050	GWP bio	DynLCA
Biogenic carbon neutrality	Yes	Yes	No	No	No
Tracks carbon flows	No	Yes	Yes	Yes	Yes
Considers storage period	No	No	Yes	Yes	Yes
Considers rotation period	No	No	No	Yes	Yes
Considers timing of emission	No	No	No	No	Yes
Important benefit	Easy to use	Easy to use	Easy to use	Static inventory	Reflects reality most
Important drawback	Biogenic carbon not considered	Storage period does not matter	Overestimation benefits	Mix of static and dynamic results	Dynamic inventory: time- and data-intensive

6. Reuse in LCA

The reuse of construction materials extends their service life beyond a single use phase, allowing biogenic carbon to remain stored in the built environment for longer periods. As discussed in Chapter 4, this extended storage affects the timing of carbon release, while Chapter 5 demonstrated that the representation of this timing depends on the chosen modelling approach.

When reuse is introduced, an additional challenge emerges: environmental impacts and benefits are no longer confined to a single life cycle but must be distributed across multiple uses. This makes it essential to clearly define how reuse is represented within Life Cycle Assessment (LCA) (Douguet & Wagner, 2021).

6.1 Preparation for reuse and system boundaries

As examined in Chapter 3, reuse involves maintaining materials or components in use without substantial transformation. In practice, however, reclaimed construction materials may temporarily be classified as waste when they are discarded, stored, or processed before their reuse potential is confirmed (Naval, 2021).

Through processes such as sorting, cleaning, inspection, and minor repair—collectively referred to as “preparation for reuse”—materials can regain product status. During this stage, only limited interventions are permitted. The fundamental composition of the material must remain intact (Naval, 2021).

Within Life Cycle Assessment (LCA), these processes are particularly relevant because they influence how reuse is represented within system boundaries and end-of-life modelling. Preparation-for-reuse activities may introduce additional impacts related to transport, dismantling, inspection, storage, and processing, while also determining whether a component leaves the system as waste or remains in circulation as a reusable product (Naval, 2021; Poncelet et al., 2023).

6.2 Representation of reuse in LCA

In a conventional LCA, a newly produced component carries the environmental burdens associated with all life cycle stages, including raw material extraction, manufacturing, transport, use, and end-of-life treatment. In contrast, a reused component enters the system after its initial production has already occurred. Instead of requiring new production, it replaces a newly manufactured component, thereby avoiding impacts associated with early life cycle stages (Douguet & Wagner, 2021).

Within the EN 15804 + A2 framework, this effect is primarily reflected in Module A, which includes production processes (A1–A3). For most construction materials, these stages account for the largest share of environmental impacts. Avoiding them therefore represents the main environmental benefit of reuse (Douguet & Wagner, 2021).

Reuse also affects Module C, which represents end-of-life processes. When components are reclaimed for reuse, demolition and waste-processing activities may be avoided in the first life cycle. These avoided impacts can be attributed to the system that enables reuse (Douguet & Wagner, 2021).

In addition, Module D can be used to account for benefits beyond the system boundary. In reuse scenarios, this may include crediting the first life cycle for delivering a component suitable for future reuse. Nevertheless, current standards provide limited guidance on how such benefits should be quantified and allocated (Delem et al., 2021).

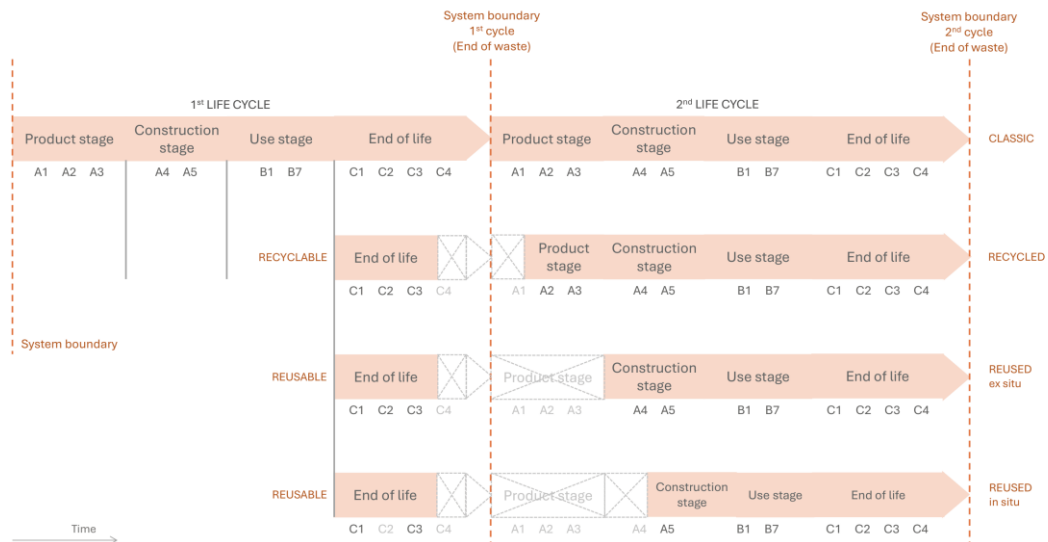


Figure 9. The impact of recycling and reuse on life cycle modules (Douguet & Wagner, 2021)

Although reclaimed components require additional processes such as disassembly, sorting, minor repair, or transport, these interventions are generally minor compared to the impacts associated with producing a new component (OVAM, 2023).

In practical LCA applications, reuse is often represented in a simplified manner. Figure 9 illustrates how recycling and reuse influence the distribution of impacts across life cycle modules. Reuse can avoid part of the production impacts in Module A, while simultaneously delaying or avoiding certain end-of-life processes within Module C. The figure also distinguishes between ex situ reuse, where elements undergo dismantling, transport, and preparation before reuse in a different location, and in situ reuse, where components are reused directly within the same building context with fewer additional processes (Douguet & Wagner, 2021).

In the Belgian tool TOTEM, reused components are typically modelled as having no production impacts, making avoided impacts in Module A directly visible. However, preparation-for-reuse processes, interactions across multiple life cycles, and benefits beyond the system boundary (Module D) are not fully represented (Ghyoot et al., 2021; OVAM, 2023).

6.3 Reuse and biogenic carbon modelling

When reuse is combined with biogenic materials such as wood, the modelling of carbon flows becomes more complex. As discussed in Chapter 5, different approaches exist to represent biogenic carbon, ranging from static to fully dynamic methods.

While these approaches differ in how they represent carbon uptake and release over time, they do not inherently define how reuse should be represented across successive life cycles. Even when dynamic modelling is applied, additional assumptions are required to determine how

extended carbon storage and delayed emissions are attributed to different users and life cycles (Van Gulck et al., 2025).

Consequently, the climate impact of reused timber is not determined solely by the chosen carbon modelling approach, but also by how environmental impacts and benefits are distributed between successive uses. This issue is addressed through allocation methods.

6.4 Allocation methods

6.4.1 Classical allocation approaches

The modelling of recycling and reuse in LCA has been discussed extensively since the 1990s. Two main approaches are commonly distinguished in practice (Finkbeiner et al., 2013):

- The recycled content (cut-off) approach, based on the principle of first responsibility
- The end-of-life (avoided burden) approach, based on the principle of last responsibility

In the cut-off approach, a product carries the full environmental burden of primary material production, while subsequent life cycles benefit from using recycled or reused materials with lower impacts. This approach incentivizes the use of secondary materials but provides no incentive to design for reuse (Finkbeiner et al., 2013).

Conversely, the end-of-life approach assigns credits to products that enable future reuse or recycling. The environmental burden of primary production is partially transferred to subsequent life cycles. This approach incentivizes circular design but may encourage excessive use of primary materials if future reuse is overestimated (Finkbeiner et al., 2013).

These two approaches represent methodological extremes. Several intermediate approaches exist, including partitioning methods that distribute impacts across life cycles based on predefined rules, such as equal sharing, economic value, or material quality (Finkbeiner et al., 2013).

6.4.2 Allocation in biogenic systems

While existing allocation methods are well established for non-biogenic materials, their application to biogenic materials introduces additional complexity (Finkbeiner et al., 2013).

For non-biogenic materials, primary production is associated with net greenhouse gas emissions. The allocation problem therefore focuses on how environmental burdens are distributed across life cycles (Finkbeiner et al., 2013).

In contrast, for biogenic materials such as wood, primary production may result in a net removal of atmospheric CO₂ due to carbon sequestration during biomass growth. As a result, the key question shifts from the allocation of burdens to the allocation of environmental benefits (Finkbeiner et al., 2013).

Current allocation approaches do not explicitly define how sequestration benefits should be distributed across successive life cycles. Applying conventional allocation methods to biogenic systems may therefore lead to substantially different results depending on how carbon uptake, storage, and release are allocated between life cycles (Finkbeiner et al., 2013).

7. Research gap

The previous chapters demonstrated that assessing reused structural timber within life cycle assessment (LCA) involves several methodological complexities.

Firstly, biogenic materials such as wood may provide important climate benefits compared to conventional fossil-based construction materials because they can temporarily remove and store atmospheric CO₂ during biomass growth. However, parameters influencing biogenic carbon storage and sequestration, such as density, carbon fraction, and rotation period, may vary substantially between wood species. At the same time, temporary carbon storage, combined with forest regrowth and delayed emissions, introduces additional methodological challenges within LCA. In contrast to fossil-based systems, the assessment of wood therefore requires the simultaneous representation of both biogenic and fossil carbon flows.

Secondly, conventional LCA approaches generally rely on static climate indicators that do not explicitly account for either biogenic carbon storage or the timing of carbon uptake and emissions. Although dynamic approaches have been developed to address this limitation, their application remains relatively limited due to their methodological complexity and the additional assumptions they require. Among fully dynamic approaches, DynLCA is therefore preferred over GWPbio, as it provides a consistent dynamic framework for both fossil and biogenic carbon flows, avoiding the mixed static-dynamic assessment inherent to GWPbio.

Finally, reuse introduces a further layer of complexity because environmental impacts and benefits must be distributed across multiple life cycles. Different allocation methods may therefore lead to substantially different results, particularly when biogenic carbon storage is involved.

While these methodological aspects have each been studied individually, fewer studies have examined their combined influence within reused structural timber.

This leads to the following research question:

- *How do methodological choices in biogenic carbon modelling and wood species influence the climate impacts of reused structural timber?*

1. Introduction

Part II outlines the methodology used to assess the climate change impact of reused structural timber within a Life Cycle Assessment (LCA) framework.

Building further on the theoretical concepts introduced in Chapter 5 of the literature review, the following chapters describe the goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation phases of the assessment. In addition, the methodological choices regarding system boundaries, biogenic carbon modelling, allocation methods, and sensitivity analyses are introduced.

2. Goal and scope

The goal and scope definition establishes the framework within which the life cycle assessment is carried out, specifying what is analysed, which processes are included, and how the results should be interpreted (Mudersbach et al., 2023).

The goal of this study is to assess how methodological choices influence the climate change impact of reused structural timber within a dynamic life cycle assessment framework. The research compares different biogenic carbon modelling approaches and allocation methods across two consecutive life cycles of structural timber. In addition, the influence of wood species and key assumptions regarding density, rotation period, and service life, is evaluated through sensitivity analyses.

The assessment is limited to reused structural timber within a European context and considers five wood species commonly found in temperate Europe: spruce, pine, larch, oak, and beech. The analysis is carried out at material level rather than building level, meaning that differences in architectural design, structural detailing, and overall building performance are not considered. This enables a controlled comparison of material-related parameters and modelling approaches. The selected wood species and corresponding material properties are discussed further in Chapter 3.

Although life cycle assessment can include multiple environmental impact categories, this study focuses exclusively on climate change impacts expressed in CO₂-equivalents (Mudersbach et al., 2023; OVAM, 2023). The examination is therefore not intended to provide a complete environmental profile, but rather a methodological comparison of how modelling choices influence climate impacts. The applied climate change assessment framework and biogenic carbon modelling approaches are discussed further in Chapter 4.

2.1 Functional unit

The functional unit is defined as 1 m³ of structural timber beam. This unit is selected because timber is commonly specified in volumetric terms and because biogenic carbon storage is directly related to the volume of wood. It also allows differences in density, carbon content, and rotation period between wood species to remain visible within the assessment.

A building-level functional unit is not applied, as this would introduce additional variables beyond the scope of the study.

2.2 System boundaries

The system boundaries define which processes are included within the life cycle assessment and therefore determine the extent of the analysis. This study follows the EN 15804+A2 framework and includes production, use, reuse, and end-of-life processes. The general structure of the EN 15804+A2 framework was introduced in the literature review (Chapter 5) and is further implemented within the life cycle inventory and impact assessment described in Chapters 3 and 4.

The study models two consecutive life cycles of the same timber element, consisting of an initial use phase (LC 1) followed by a second use phase after reuse (LC 2). A 100-year time horizon is applied, within which both life cycles and the associated carbon flows are evaluated.

The assessment includes modules A (production and construction) and C (end-of-life), as well as processes associated with reuse between both life cycles. Module B and Module D are not assessed separately within this study. Module B is excluded as structural timber beams do not typically require maintenance or replacement during their service life, making this module difficult to assess in a comparative context. Module D is excluded as the associated benefits are instead explicitly assessed within the defined system boundaries.

Production-related impacts (Module A) are assigned to the first life cycle (LC 1), while reuse processes and end-of-life impacts (Module C) are allocated to the second life cycle (LC 2). The allocation of biogenic carbon flows between both life cycles depends on the applied allocation method and is discussed further in Chapter 4.

The defined system boundaries ensure that all relevant processes contributing to the climate change impact of the timber element are consistently included (OVAM, 2023).

2.3 Service life

A service life of 50 years is assigned to both life cycles, allowing the two consecutive life cycles to be represented within the applied 100-year assessment period. As discussed in Chapter 5 of the literature review, Dynamic LCA explicitly considers the timing of carbon uptake and release over time. Service life therefore directly influences the calculated climate impacts within the dynamic assessment framework.

Although structural timber elements may remain in use for substantially longer periods, reuse scenarios involve uncertainties related to dismantling, material quality, future reuse potential, and changing building requirements (Douguet & Wagner, 2021; Feys & Defever, 2025). Additional sensitivity analyses are therefore performed using alternative service life assumptions. The influence of service life within the dynamic assessment is evaluated further in Chapter 5.

3. Life cycle inventory (LCI)

The life cycle inventory (LCI) compiles all material and energy flows associated with the system under study. In this research, the inventory is developed using the SimaPro software, which enables the modelling of complex product systems and the calculation of environmental impacts (Goedkoop et al., 2016).

The model is primarily based on data obtained from the Ecoinvent 3 database, which contains datasets describing industrial processes, energy systems, transport, and waste treatment. These datasets allow the construction of complete supply chains and ensure consistency in background processes across the model.

Within SimaPro, the study consistently applies system processes. These aggregate upstream supply chains into a single dataset, providing an appropriate level of detail for comparative analysis without introducing unnecessary complexity. All data are linked to the defined functional unit of 1 m³ of structural timber.

In addition to database information, relevant data from literature sources and Environmental Product Declarations (EPDs) are used to refine specific processes, particularly for timber production and reuse-related activities. This combination of sources ensures both general applicability and sufficient specificity for the research context.

The inventory represents a system consisting of two consecutive life cycles, including primary production, use, reuse processes, and end-of-life treatment. The following sections describe the selected wood species, material properties, modelling assumptions, and inventory processes included within both the new production and reuse scenarios.

3.1 Wood species

This research focuses on the climate impact of reused structural timber within a European context. Only wood species commonly used in the European temperate climate are considered. As discussed in Chapter 4 of the literature review, the modelling of biogenic carbon depends strongly on parameters related to carbon storage and biomass growth. Since these characteristics may vary substantially between wood species, comparing multiple species provides additional insight into how species-specific properties influence the climate impacts.

Both softwood and hardwood species are structurally applied within Europe, although softwoods remain more widely used in contemporary construction practice (Jeffree & de Munck, 2019; Rotor vzw, 2021). To reflect this distribution, this study includes three softwood species and two hardwood species.

The selection of species is based on both literature and observations of the reuse market. Previous studies identify spruce, pine, and larch as commonly used and reused softwoods, and oak and beech are considered representative hardwood species in Europe (Jeffree & de Munck, 2019). This array is further supported by observations from the Belgian reuse platform Opalis, where reclaimed structural timber in these species is frequently available at dealerships like Trovo and RecupHout (Opalis, 2026).

3.2 Material properties

To perform the life cycle assessment, a set of material-specific parameters must be defined for each wood species. The most relevant parameters in this study are density, rotation period, and carbon fraction, as these directly influence fossil emissions, biogenic carbon storage, and temporal carbon flows, as discussed in section 4.4 of the literature review.

The selected parameters vary between species and across literature sources. To ensure consistent comparison between wood species, representative baseline values are defined for each parameter, while additional sensitivity analyses are performed to evaluate the influence of parameter variability on the results.

The following sections describe the selected parameters, the consulted data sources, and the assumptions applied within the assessment.

3.2.1 Density

Density is a key parameter influencing the environmental impact of timber, as it determines the mass of material associated with the functional unit. Since many production, transport, and processing impacts are mass-dependent, density directly affects both fossil greenhouse gas emissions and the amount of stored biogenic carbon.

Reported density values vary depending on the source, geographical context, and measurement conditions. To establish representative values for each species, data from multiple literature sources were compared. Initial values were obtained from a technical report on European forests published by the Joint Research Centre (Blujdea et al., 2024). These were subsequently compared with the studies conducted by Petráš et al. on softwood and hardwood densities in Europe (Petráš et al., 2019, 2020).

Table 3 provides an overview of the selected density values for the five wood species.

Table 3. Overview of densities

Source:		Joint Research Centre (Blujdea et al., 2024)							Petráš et al., 2019, 2020	Median	
Wood species		Belgium	The Netherlands	Germany	France	Denmark	Austria	Luxembourg	-	-	
Picea Abies	Spruce	380	380	470	380	380	400	400	484,80	390	kg/m ³
Pinus sylvestris	Pine	420	420	320	430	380	420	-	477,60	420	kg/m ³
Larix decidua	Larch	440	450	370	-	-	460	-	566,82	450	kg/m ³
Quercus Robur	Oak	540	570	540	560	560	580	580	728,50	565	kg/m ³
Fagus Sylvatica	Beech	590	620	530	560	560	580	580	694,64	580	kg/m ³

Despite variations between sources, several general trends can be identified. Softwood species such as spruce and pine typically show lower densities, larch shows intermediate values, and hardwood species such as oak and beech generally exhibit higher densities.

The density values reported by Petráš et al. are consistently higher than those reported by the Joint Research Centre. To ensure comparability between species while limiting the influence of outliers, a baseline scenario is defined using the median value across sources for each species. In addition, sensitivity analyses are conducted using minimum and maximum density values in order to evaluate the influence of density variation on the climate impacts.

3.2.2 Rotation period

The rotation period is defined as the time required for forest biomass to regenerate and reabsorb the carbon removed during harvesting. As discussed in the literature review (sections 4.3 and 5.6), this parameter directly influences the temporal distribution of biogenic carbon uptake and is particularly relevant for the Regrowth approach, where carbon sequestration occurs progressively over time.

Rotation period values were obtained from literature sources and compared across species and geographical contexts. Table 4 presents the selected values based on the Joint Research Centre report (Blujdea et al., 2024).

Table 4. Overview of rotation periods

Source:		Joint Research Centre (Blujdea et al., 2024)							Median
Wood species		Belgium	The Netherlands	Germany	France	Denmark	Austria	Luxembourg	-
Picea Abies	Spruce	50	60	80	70	-	110	60	65
Pinus sylvestris	Pine	40	50	80	70	-	80	-	70
Larix decidua	Larch	55	60	80	-	-	120	-	70
Quercus Robur	Oak	-	65	80	110	-	80	200	80
Fagus Sylvatica	Beech	-	65	80	110	-	110	160	110

Years
Years
Years
Years
Years

Rotation periods vary significantly between countries and are influenced not only by tree species, but also by forest management practices and harvesting strategies. Nevertheless, several general trends can be observed, with softwood species generally showing shorter rotation periods than hardwood species.

To ensure consistency between species, baseline values are defined using the median rotation period for each species. Additional sensitivity analyses are performed using minimum and maximum values to assess the influence of rotation period assumptions on the calculated climate impacts.

3.2.3 Carbon fraction

The carbon fraction represents the proportion of dry biomass consisting of elemental carbon. As discussed in Section 4.4 of the literature review, this parameter directly determines the amount of biogenic carbon stored within the timber material and therefore influences the calculation of carbon uptake and release.

Although a default carbon fraction of 50% is commonly applied in LCA studies and guidelines for wood products, this research uses species-specific values to enable a more detailed comparison between wood species. While differences between species are relatively limited, these variations directly affect the amount of stored biogenic carbon and are therefore included within the assessment (Horan et al., 2025).

The selected values are based on the global database of woody tissue carbon concentrations developed by Doraisami et al. (2022), using values representative for temperate European conditions. In contrast to density and rotation period, variations in carbon fraction between literature sources are relatively limited. For this reason, a single representative value is selected for each species rather than applying minimum and maximum sensitivity ranges (Doraisami et al., 2022).

Within the dataset, spruce and pine generally show slightly higher carbon fractions, larch somewhat lower values, and oak and beech intermediate to higher values. Table 5 presents the selected carbon fraction values for the five wood species.

Table 5. Overview of carbon fractions

Source:		Doraisami et al., 2022	
Wood species		-	
Picea Abies	Spruce	50,42	%
Pinus sylvestris	Pine	48,90	%
Larix decidua	Larch	45,50	%
Quercus Robur	Oak	47,20	%
Fagus Sylvatica	Beech	47,33	%

The selected material properties form the basis for the life cycle inventory model described in the following sections, where they influence both production-related impacts and the modelling of biogenic carbon flows.

3.3 New production system

A conventional newly produced structural timber beam is modelled to represent the impacts associated with primary timber production. This production system is included throughout the assessed scenarios in order to evaluate the influence of reuse and allocation choices on the climate change impact.

The modelling approach is primarily based on the Belgian TOTEM methodology, as described in *Environmental Profile of Building Elements* (OVAM, 2023). This ensures consistency with current Belgian LCA practice and with the EN 15804+A2 framework applied throughout this study. Where additional specificity is required, the methodology is complemented with literature sources and Environmental Product Declarations (EPDs).

In particular, an Environmental Product Declaration for solid structural timber developed by Hout Info Bois is used to refine several assumptions related to timber production and packaging processes (Hout Info Bois, 2025). This EPD was developed for the Belgian context using data from multiple manufacturers located in Wallonia and provides cradle-to-grave environmental information for 1 m³ of structural timber.

The new production system includes production (A1–A3), transport to site (A4), construction-related processes (A5), and end-of-life processes (C1–C4). Module D is excluded from the assessment, consistent with the system boundaries defined in Chapter 2.

Because the focus of this study lies on the influence of biogenic carbon modelling approaches and allocation methods, the production system is represented using standardized and representative assumptions rather than detailed process-specific modelling. Detailed information regarding the applied processes, assumptions, parameter values, and inventory data is provided in Appendix D.

3.3.1 Production phase (A1-A3)

For the production phase, representative timber production processes are selected from the Ecoinvent database. Separate datasets are used for softwood and hardwood beams:

- *Sawnwood, beam, softwood, dried ($u=10\%$), planed {Europe without Switzerland} | Cut-off, S*
- *Sawnwood, beam, hardwood, dried ($u=10\%$), planed {Europe without Switzerland} | Cut-off, S*

These processes represent average European production conditions and correspond to the geographical scope of this study. The datasets provide environmental impacts per cubic metre, corresponding to the functional unit applied in this study. However, they assume fixed reference densities of 424.4 kg/m^3 for softwood and 614.4 kg/m^3 for hardwood. Since this research compares multiple wood species with different densities, the production impacts are linearly rescaled according to the species-specific densities defined in Section 3.2.1.

This scaling ensures consistency between the background datasets and the species-specific foreground system.

3.3.2 Transport to site (A4)

Transport impacts between the production facility and the construction site are modelled according to standardized assumptions derived from the Belgian PCR and the TOTEM methodology (OVAM, 2023).

Structural timber beams are classified as prefabricated structural products, resulting in a single transport stage between factory and construction site. A transport distance of 100 km is assumed using a 16–32 tonne diesel lorry.

The following Ecoinvent dataset is applied:

- *Transport, freight, lorry, 16–32 metric ton, diesel, EURO 5 {RER} | Cut-off, S*

Transport impacts are calculated in ton-kilometres (tkm) and therefore vary depending on the weight of the timber beam, which is directly influenced by species-specific density.

3.3.3 Installation phase and auxiliary materials (A5)

Within the construction phase (A5), packaging materials are included as auxiliary inputs. In contrast to the TOTEM methodology, where such materials are not explicitly considered, this study includes polyethylene (PE) film and polypropylene (PP) strapping based on assumptions from the Hout Info Bois EPD (2025). These materials are included to ensure consistency with the reuse scenarios discussed in Section 3.4, where packaging and auxiliary materials are also considered.

The quantities specified in the EPD are based on a reference density of 453.9 kg/m^3 . To maintain consistency with the species-specific modelling approach applied throughout this study, these values are linearly rescaled according to timber density.

Table 6. Overview of auxiliary materials used in the new production system

Material	Production process	Transport category	Waste category	Landfill process	Incineration process
PE film	Packaging film, low density polyethylene (RER) packaging film production, low density polyethylene Cut-off, S	Loose products	Polyolefins (PP, PE)	Waste polyethylene (CH) treatment of waste polyethylene, sanitary landfill Cut-off, S	Waste polyethylene (CH) treatment of waste polyethylene, municipal incineration FAE Cut-off, S
Plastic strapping	Polypropylene, granulate (RER) polypropylene production, granulate Cut-off, S	Loose products	Polyolefins (PP, PE)	Waste polypropylene (CH) treatment of waste polypropylene, sanitary landfill Cut-off, S	Waste polypropylene (CH) treatment of waste polypropylene, municipal incineration FAE Cut-off, S

The referenced EPD also includes crane use during installation. However, this process is excluded from the assessment. Crane operations strongly depend on project-specific conditions and are therefore considered insufficiently representative for comparative analysis. In addition, excluding crane use ensures consistency with the modelling assumptions applied for the reuse scenarios discussed in Section 3.4.

In addition, a material loss factor of 5% is applied during installation, consistent with the TOTEM methodology (OVAM, 2023).

3.3.4 End-of-life phase (C1-C4)

The end-of-life phase is modelled according to the assumptions applied within the TOTEM methodology (OVAM, 2023). Structural timber is assumed to be destructively dismantled at the end of its service life and subsequently transported for waste treatment using the same transport process applied in module A4. Detailed transport distances and process calculations are included in Appendix D and E.

In this study, 100% of the timber is assumed to be incinerated at end-of-life using the following Ecoinvent process:

- *Waste wood, untreated {CH} | municipal incineration | Cut-off, S*

No separate impacts are assigned to module C3, as no additional waste processing is considered prior to incineration. Full incineration is assumed to ensure that the complete biogenic carbon content of the timber element is released at end-of-life, maintaining consistency with the applied biogenic carbon modelling framework and providing a consistent basis for comparing the timing of carbon release across species and allocation methods. This differs from methodologies such as TOTEM, where a portion of the timber is assumed to be recycled rather than fully incinerated.

3.4 Reuse scenarios

To model the transition between the first and second life cycle (LC 1 and LC 2), reuse processes are included within the assessment. These processes represent the reclamation, preparation, transport, and reintegration of reused timber elements into a new construction application.

The modelling approach is based on a master's thesis by Feys & Defever (2025), in which seven real-life case studies of glulam beam reuse were analysed. Based on these observations, four representative reuse scenarios were developed, each corresponding to a different degree of intervention and processing complexity (Feys & Defever, 2025).

Within this study, Scenario II is used as the baseline reuse scenario. The remaining scenarios are evaluated as part of a sensitivity analysis to assess the influence of alternative reuse pathways on the calculated climate impacts.

3.4.1 Scenario I

Scenario I represents a direct reuse pathway. After dismantling, the beam is transported directly to the new construction site. Apart from cutting to size, no mechanical processing is applied (Feys & Defever, 2025).

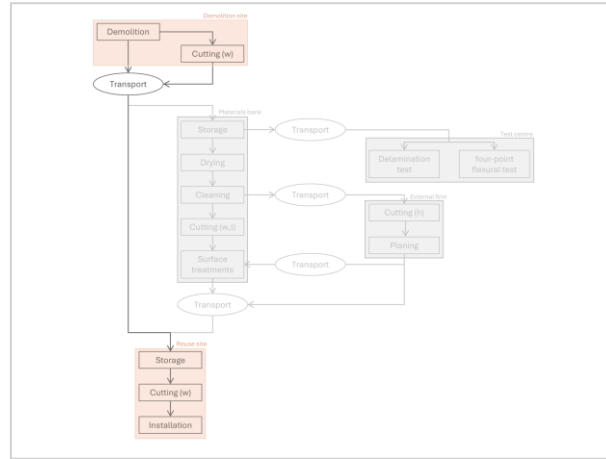


Figure 10. Process flow diagrams for reuse scenario I (Feys & Defever, 2025)

3.4.2 Scenario II

Scenario II includes an intermediate storage phase. After dismantling, the beam is transported to a material bank or contractor storage facility before being transported to the new construction site. Additional cleaning and preparation activities are included, although no structural testing is performed (Feys & Defever, 2025). This scenario is used as the baseline reuse scenario throughout the study.

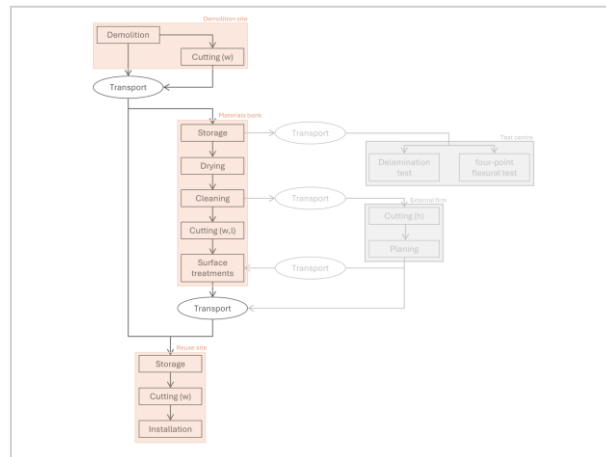


Figure 11. Process flow diagrams for reuse scenario II (Feys & Defever, 2025)

3.4.3 Scenario III

Scenario III extends Scenario II with additional mechanical processing like planing and cutting and structural testing activities. These activities typically require transport to specialized facilities (Feys & Defever, 2025).

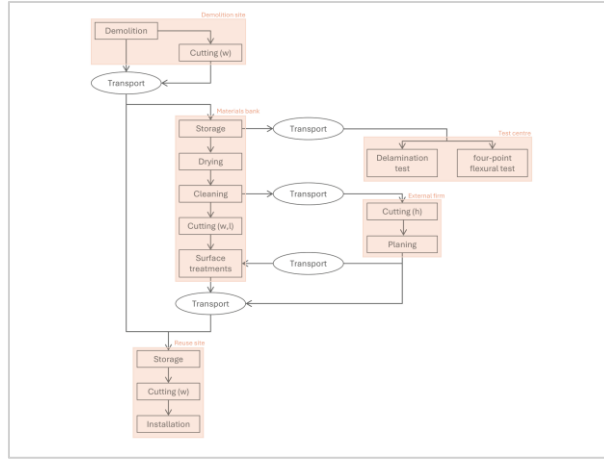


Figure 12. Process flow diagrams for reuse scenario III (Feys & Defever, 2025)

3.4.4 Scenario IV

Scenario IV differs fundamentally from the other scenarios as it represents in-situ reuse, where timber elements are reused within the same building context, avoiding external transport while still applying the same surface treatments as Scenario II (Feys & Defever, 2025).

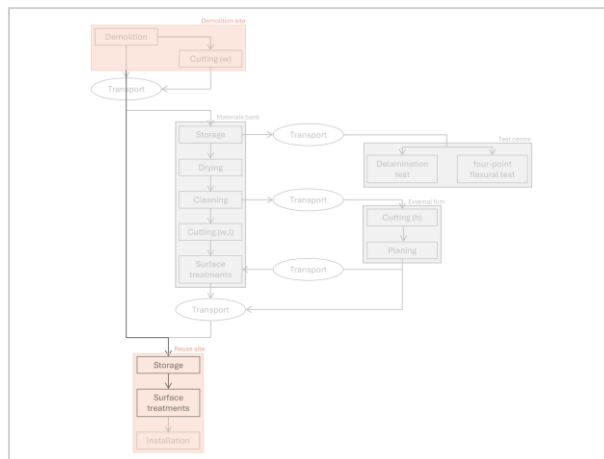


Figure 13. Process flow diagrams for reuse scenario IV (Feys & Defever, 2025)

3.4.5 General modelling assumptions

The original case studies by Feys & Defever (2025) focused on glulam beams with a reference density of approximately 420 kg/m^3 . Since this study compares multiple solid timber species with different densities, reuse-related impacts are rescaled to maintain consistency with the functional unit and the new production system. This scaling is applied to transport impacts, auxiliary material quantities, and other mass-dependent processes. Transport processes are modelled using the same Ecoinvent transport dataset applied in module A4 of the new production system.

Several reclamation and surface treatment activities involve electrically driven equipment. Table 7 provides an overview of the included machining and processing operations. Besides electricity consumption, high-pressure cleaning additionally accounts for water consumption (Feys & Defever, 2025).

Table 7. Machining and processing activities applied during reclamation processes

Machine use
Removing metal elements with a metal detector
Cutting widthwise with a hand-held circular saw
Making openings ($\pm 12x$) with a hammer drill with stand
Cleaning surfaces with an electric wire brush
Cleaning surfaces with a high-pressure cleaner (electricity fraction)
Cleaning surfaces with a parquet sanding machine
Abrasive blasting

Not all electrically driven activities observed by Feys & Defever (2025) in the reuse scenarios are included within this assessment. Processes related to demolition, installation, lifting operations, or on-site transportation are excluded because these strongly depend on project-specific conditions and would not be representative for comparative analysis.

Auxiliary materials used during reclamation processes are also included within the assessment. These consist of protective covers used during storage and transport, together with coatings and surface treatment products applied to reclaimed timber elements. Both production and end-of-life impacts of these materials are included (Feys & Defever, 2025).

Table 8. Auxiliary materials used during reclamation processes

Material
Waterproof cover (PE)
(Fire-resistant) paint
Varnish
linseed oil
Epoxy resin

Detailed inventory data, process assumptions, transport distances, excluded processes, and applied Ecoinvent datasets are provided in Appendix D.

4. Life cycle impact assessment (LCIA)

4.1 Climate change indicator

The life cycle impact assessment (LCIA) phase translates inventory flows into environmental impact indicators. Within this study, impacts are expressed exclusively through the climate change indicator in kg CO₂-equivalents rather than aggregated environmental scores such as mPt.

As discussed in Chapter 5 of the literature review, climate change impacts in Life Cycle Assessment (LCA) are commonly evaluated using Global Warming Potential (GWP)-based characterization factors. Fossil greenhouse gas emissions associated with production, transport, processing, reuse, and end-of-life activities are quantified using the applied Ecoinvent datasets described in Sections 3.3 and 3.4.

In addition to fossil emissions, the evaluation explicitly includes biogenic carbon storage and release associated with timber growth and end-of-life treatment. Because these carbon flows occur at different moments in time, Dynamic Life Cycle Assessment (DynLCA) is applied to account for the temporal distribution of emissions and removals, as discussed in Section 5.6 of the literature review.

The following sections describe the applied biogenic carbon calculations, dynamic characterization approach, and allocation methods used within the assessment.

4.2 Biogenic carbon calculation

The amount of biogenic carbon stored within timber is determined based on the dry mass of the wood and its corresponding carbon fraction. As examined in Section 3.2, both density and carbon fraction vary between wood species and therefore directly influence the amount of stored biogenic carbon.

The stored carbon is converted into CO₂-equivalents using the molecular weight ratio between carbon and carbon dioxide (44/12) (Horan et al., 2025). The total amount of biogenic carbon stored within the functional unit is calculated as:

$$Impact = u \cdot CF \cdot \frac{44}{12}$$

where:

- u = mass of dry wood
- CF = carbon fraction
- $\frac{44}{12}$ = conversion factor from carbon to CO₂

Within the assessment, carbon uptake is represented as a negative emission, while its release at the end of the service life is represented as a positive emission.

4.3 Dynamic assessment approach

To account for the temporal distribution of greenhouse gas emissions and removals, this study applies a Dynamic Life Cycle Assessment (DynLCA) approach. As discussed in Chapter 5 of the literature review, dynamic assessment methods evaluate emissions differently depending on when they occur within the selected time horizon.

Within DynLCA, greenhouse gas emissions and removals are characterized using dynamic characterization factors (DCF), which decrease over time within the assessment period. As a result, emissions occurring later in the life cycle receive a lower climate impact than emissions occurring earlier in time, allowing temporary carbon storage and delayed emissions to be explicitly reflected within the assessment.

A time horizon of 100 years is applied throughout the assessment, consistent with conventional GWP100 practice. However, unlike static approaches, the dynamic framework explicitly accounts for the timing of carbon uptake and release within this period.

The dynamic characterization factors applied in this study are based on the Bern carbon cycle model described by Levasseur et al. (2010) and Resch et al. (2021). Figure 14 illustrates the evolution of the applied dynamic characterization factors over the 100-year time horizon. The complete set of applied DCF values is included in Appendix C.

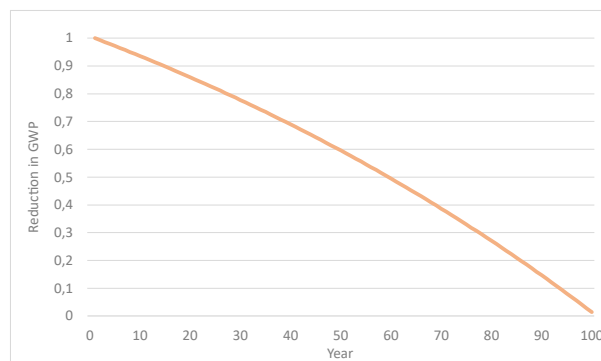


Figure 14. Dynamic characterization factors (DCF) over the 100-year time horizon (Resch et al., 2021)

4.4 Carbon sequestration scenarios

As mentioned in Chapter 5 of the literature review, different assumptions regarding the timing of carbon uptake can lead to substantially different carbon flow trajectories within dynamic biogenic carbon assessments. To evaluate the influence of these assumptions, this study applies both the Growth and Regrowth approaches.

In the Growth approach, biogenic carbon sequestration is treated as an instantaneous carbon uptake occurring before the assessed biomass enters the system boundary. In contrast, the Regrowth approach distributes carbon sequestration progressively over time following biomass harvest, making carbon uptake dependent on the assumed forest rotation period.

4.4.1 Regrowth modelling

To represent this temporal distribution of biomass growth, this study applies the Chapman–Richards growth function, which is commonly used to describe tree growth over time (Von Dufving et al., 2026).

The growth function distributes the total amount of biogenic carbon uptake across the rotation period instead of representing sequestration as a single event. In this way, carbon uptake can be modelled consistently within the dynamic assessment framework. The applied growth function is defined as:

$$f_{CR}(y) = k \cdot p \cdot e^{-k \cdot y} \cdot (1 - e^{-k \cdot y})^{p-1}$$

where:

- k = growth rate parameter (0,023)
- p = catabolism parameter (3)
- y = year within rotation period

The values for k and p are adopted from Von Dufving et al. (2026). The resulting growth distribution is subsequently used to allocate the total amount of carbon uptake over time:

$$f_{bio,i}(y) = m_{co2,i} \cdot f_{CR}(y) / \sum_{y=0}^{RP} f_{CR}(y)$$

where:

- $f_{bio,i}(y)$ = carbon uptake assigned to year y
- $m_{co2,i}$ = total biogenic carbon content of the timber element
- RP = rotation period

This approach allows differences in rotation period between wood species to be explicitly incorporated into the dynamic assessment.

4.5 Allocation method

Reuse introduces multiple life cycles for a single physical material. As a result, the environmental impacts and biogenic carbon flows associated with the timber element must be distributed across successive life cycles. This process is referred to as allocation (Ghyoot et al., 2021).

As discussed in Chapter 6 of the literature review, allocation plays a central role in the assessment of reused biogenic materials because different allocation choices may lead to substantially different climate impact results, even for identical reuse systems.

Allocation is applied across two consecutive life cycles: the initial application (LC 1) and the reuse phase (LC 2). The allocation methods mainly differ in how biogenic carbon uptake and release are assigned between these life cycles, while fossil greenhouse gas emissions remain allocated to the life cycle in which they occur.

Separate allocation approaches are evaluated for the Growth and Regrowth sequestration scenarios. The selected methods are primarily based on the allocation approaches discussed by Finkbeiner et al. (2013) and Hoxha et al. (2020).

4.5.1 Growth allocation methods

For the Growth approach, carbon uptake is assumed to occur before the product enters the assessed system. Allocation therefore mainly concerns how the pre-existing carbon uptake and the subsequent carbon release are distributed between life cycles.

Method G1: Common practice method

In the common practice method, the biogenic carbon uptake that occurs prior to the assessed system is fully assigned to the first life cycle (LC 1). The corresponding biogenic carbon release is also attributed to LC 1, regardless of when the physical emission occurs.

Fossil greenhouse gas emissions remain allocated to the life cycle in which they occur. As a result, the second life cycle only includes impacts related to reuse and end-of-life processes and does not contain any biogenic carbon flows. This method therefore reflects conventional LCA practice, where the initial application carries the full biogenic carbon profile of the material.

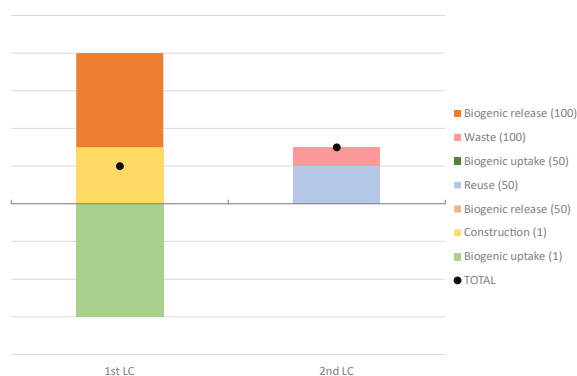


Figure 15. Allocation method G1

Method G2: Polluter-pays method

In the polluter-pays method, impacts are allocated based on the moment at which emissions occur. Carbon uptake is attributed to the first life cycle, while carbon release is assigned to the life cycle in which the emission to the atmosphere takes place.

Consequently, when reuse extends the lifetime of the material, the carbon release and associated end-of-life processes are attributed to the second life cycle. The first life cycle therefore receives the benefit of carbon uptake, while the second life cycle carries the burden of release. This method emphasizes temporal responsibility by linking emissions to the life cycle in which they occur.

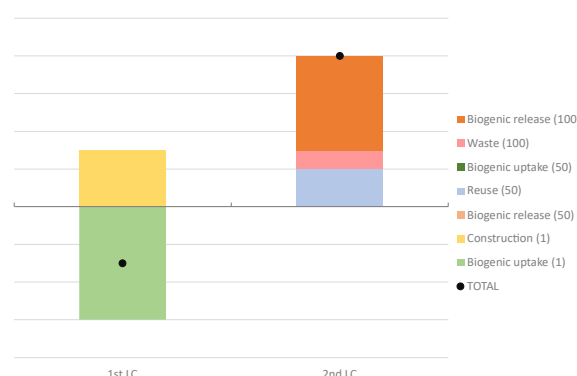


Figure 16. Allocation method G2

Method G3: Conservative method

The conservative method allocates impacts based on responsibility rather than timing. As a result, responsibility for the biogenic carbon release is assigned to the first life cycle (LC 1), even though the physical emission occurs after reuse.

The second life cycle is credited for extending the carbon storage period but does not carry the associated biogenic carbon release. Fossil emissions related to reuse and end-of-life processes remain allocated to the life cycle in which they occur. This results in a higher environmental burden for the first life cycle and a lower burden for the second.

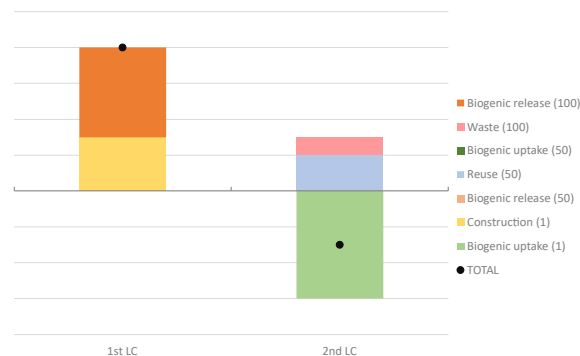


Figure 17. Allocation method G3

Method G4: Partitioning method

In the partitioning method, both carbon uptake and carbon release are shared between the two life cycles according to a predefined allocation rule. Instead of assigning the full benefit or burden to a single life cycle, each life cycle receives a share of the total uptake and release, in this case half of the total.

Production, reuse and end-of-life processes are still allocated separately. This method provides a balanced representation of impacts across life cycles but depends on assumptions regarding how the distribution is defined.

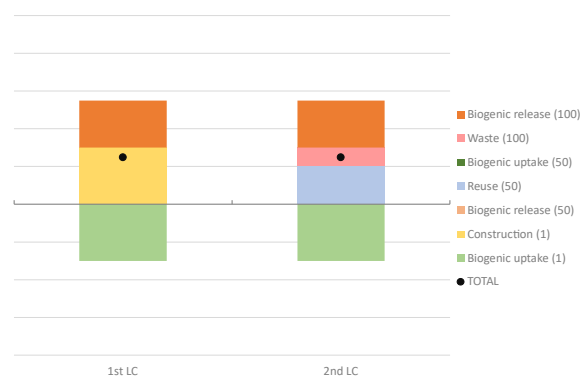


Figure 18. Allocation method G4

Method G5: Separate cycles

This method is introduced in this study to avoid dependence of the first life cycle on assumptions about future reuse while preserving carbon neutrality within each life cycle. In this method, the biogenic carbon cycle is applied separately to both life cycles. In LC 1, carbon uptake is assigned at the start of the life cycle and carbon release at the end of that life cycle. In LC 2, the same carbon uptake is taken over again and followed by release at the end of the second life cycle.

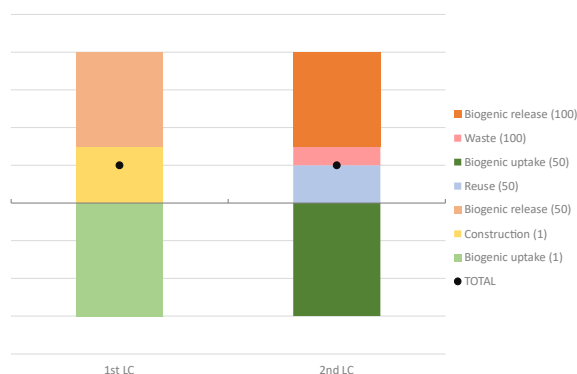


Figure 19. Allocation method G5

As a result, uptake and release are not shared between life cycles. Instead, each life cycle is assigned its own complete uptake–release pair. This allows each life cycle to be evaluated independently, without requiring knowledge of future reuse. Within dynamic modelling, this leads to different weighting of emissions and removals due to their timing.

4.5.2 Regrowth allocation methods

For the Regrowth approach, allocation additionally depends on the temporal distribution of carbon uptake during biomass regrowth.

Method R1: Common practice

This method follows the same logic as G1. Both carbon uptake and release are fully attributed to the first life cycle. This includes carbon sequestration that occurs during the second life cycle, which is still credited to LC 1.

The second life cycle therefore includes reuse and end-of-life related impacts only. This method mirrors conventional practice.

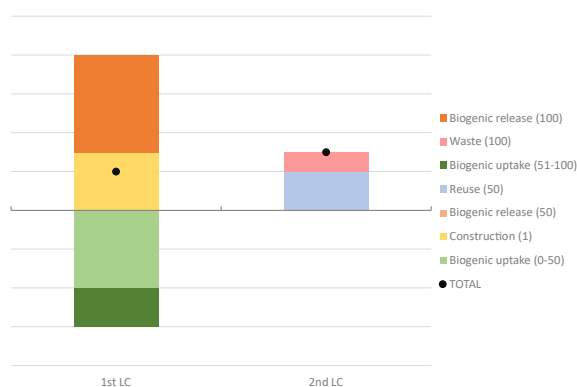


Figure 20. Allocation method R1

Method R2: Time-based split method

In the time-based split approach, carbon uptake is allocated according to when it occurs. Uptake taking place during the first life cycle is assigned to LC 1, while uptake occurring during the second life cycle is assigned to LC 2.

Each life cycle bears the full biogenic carbon release occurring at its end, independent of what happens in subsequent life cycles. As the physical release of stored carbon is independent of forest regrowth occurring elsewhere, both life cycles therefore include a complete release event corresponding to the full carbon content of the timber element. This method ensures consistency between the timing of biogenic carbon flows and their allocation across life cycles.

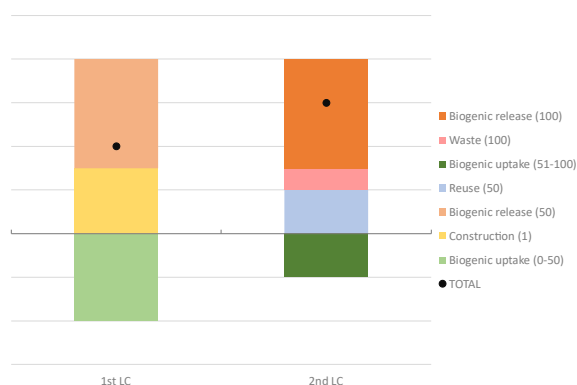


Figure 21. Allocation method R2

Method R3: Partitioning method

This method follows the same logic as G4. In the partitioning method, both carbon uptake and carbon release are distributed across the two life cycles according to a predefined allocation rule.

Instead of assigning the full benefit or burden to a single life cycle, each life cycle receives a share of the total uptake and release. Production, reuse and end-of-life processes are still allocated separately.

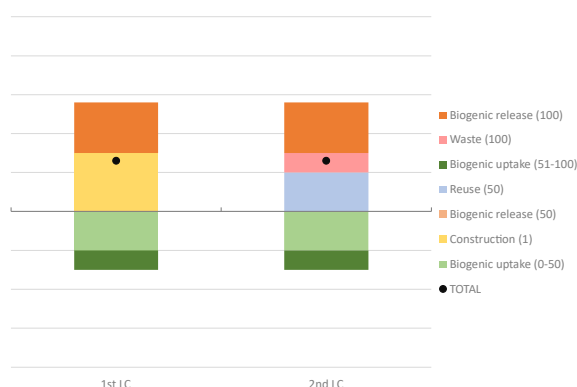


Figure 22. Allocation method R3

4.5.3 Summary

The presented allocation methods differ fundamentally in how they distribute biogenic carbon uptake and release across successive life cycles. Consequently, identical reuse scenarios may lead to substantially different climate impact results depending on the selected allocation method.

Methods G1 and R1 follow conventional LCA practice by assigning the complete biogenic carbon profile to the first life cycle. Since carbon uptake is fully credited to LC 1, these methods strongly favour the initial application of biobased materials and do not require assumptions regarding future reuse scenarios. However, the second life cycle consequently receives little or no biogenic carbon benefit.

Method G2 allocates biogenic carbon flows according to the moment at which they physically occur and therefore provides the most temporally consistent representation within the dynamic assessment framework. Carbon uptake and release are directly linked to their timing, making this method particularly suitable when the objective of the LCA is to represent carbon flows as realistically as possible over time.

Method G3 intentionally favours reuse by assigning the burden of carbon release to the first application while allowing the reuse phase to benefit from extended carbon storage. However, this may create a disproportionately high impact for the first life cycle. In addition, if the expected reuse phase does not occur in practice, part of the intended carbon benefit may effectively be lost while the associated burden has already been assigned.

Partitioning methods such as G4 and R3 attempt to distribute benefits and burdens more equally between life cycles. Since carbon uptake always occurs before release within the dynamic framework, sharing both uptake and release generally results in a net benefit for both life cycles. However, these methods depend strongly on assumptions regarding future service lives and reuse scenarios, which may not always be known reliably at the start of the assessment.

Methods G5 and R2 both treat each life cycle as independent in terms of biogenic carbon release, with each life cycle bearing a full release event at its end, independent of what happens in subsequent life cycles. This reduces dependence on assumptions regarding future reuse and simplifies modelling, while still providing carbon storage benefits to both life cycles through delayed emissions. Both methods also credit each life cycle with its own carbon uptake: in G5, both life cycles receive the full sequestration credit under the growth approach, while in R2, carbon uptake is credited to the life cycle in which sequestration physically occurs.

The selection of an allocation method therefore depends strongly on the objective of the assessment. Some methods prioritize temporal realism, others aim to promote reuse or biobased construction, while partitioning methods focus more on distributing benefits and burdens between users and life cycles. Allocation consequently represents one of the central methodological variables within the assessment of reused biogenic materials and forms a key focus of this study.

5. Interpretation

The interpretation phase involves analysing and evaluating the results of the life cycle assessment in relation to the defined goal and scope of the study (Hauschild et al., 2018; Mudersbach et al., 2023). Within this research, the interpretation primarily focuses on comparing the influence of different biogenic carbon modelling approaches, allocation methods, wood species, and temporal assumptions on the climate change impact of reused structural timber.

Because the study has a methodological focus, results are mainly interpreted in relative terms. Differences between scenarios are therefore considered more relevant than absolute impact values, as they illustrate the sensitivity of the assessment to specific modelling assumptions. Additional sensitivity analyses are performed for density, rotation period, service life, and reuse scenarios in order to evaluate their influence on the calculated results.

Finally, the interpretation considers the main limitations and uncertainties of the assessment, including assumptions related to reuse processes, aggregated background datasets, and the exclusive focus on the climate change indicator.

1. Baseline scenario

1.1 Introduction

This chapter presents the baseline scenario used throughout the study. The assessment is performed for the five selected wood species using the median density and rotation period values defined in Part II. A service life of 50 years is assumed for both life cycles, resulting in a total assessment period of 100 years.

Reuse scenario II is used as the reference reuse pathway. This scenario includes transport to a material bank, intermediate storage, and surface treatment processes prior to reuse.

The chapter first presents the fossil and biogenic carbon emissions associated with the baseline scenario. Subsequently, the allocation methods defined for the growth and regrowth approaches are compared using dynamic life cycle assessment (DynLCA).

1.2 Fossil carbon emissions

This section presents the fossil carbon emissions associated with the production, reuse, and end-of-life stages for the five selected wood species.

1.2.1 Production impact

Figure 23 shows the fossil carbon emissions associated with the production stage (A1–A5).

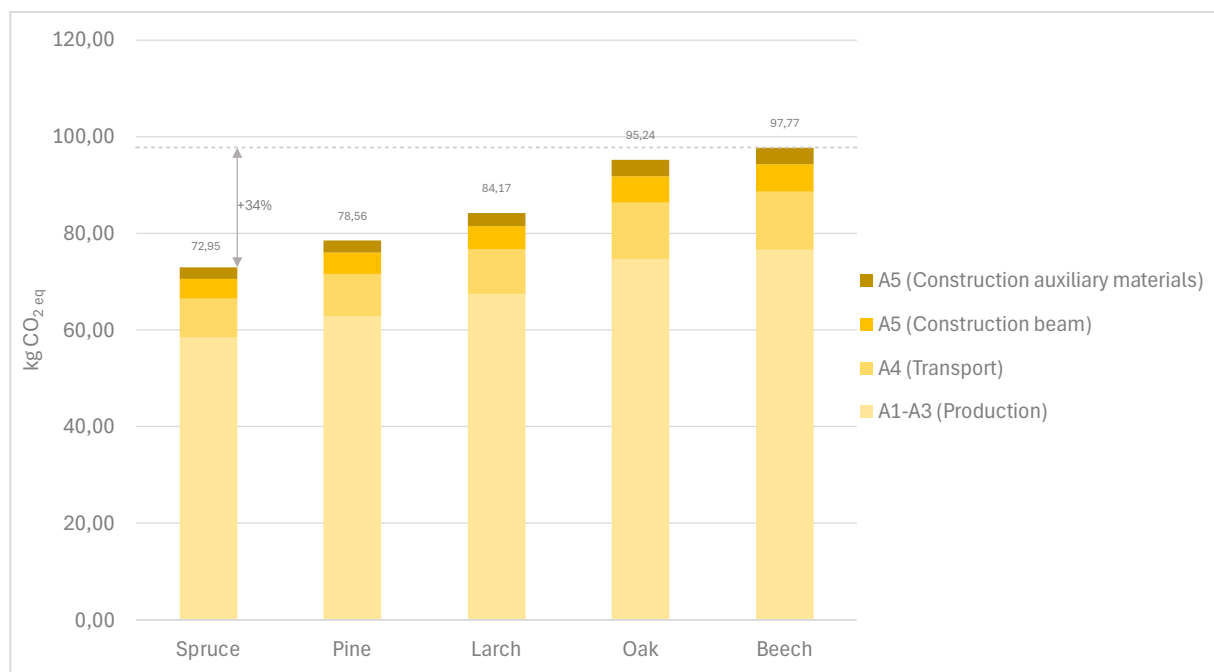


Figure 23. Fossil carbon emissions associated with the production stage (A1–A5) for the selected wood species

The production processes (A1–A3) dominate the total impact, while transport (A4) and construction processes (A5) contribute only marginally. Within module A5, a distinction is made between beam installation and packaging materials, with the latter also including the end-of-life treatment of the packaging materials as defined in the selected EPD datasets.

The results show a clear increase in impact with density. In this dataset, oak and beech result in higher impacts than the selected softwood species. Beech results in the highest impact, approximately 34% higher than spruce, reflecting the difference in material mass for 1 m³ of structural timber.

1.2.2 Reuse impact

Figure 24 compares the fossil carbon emissions of reuse scenario II with the impact of a new beam.

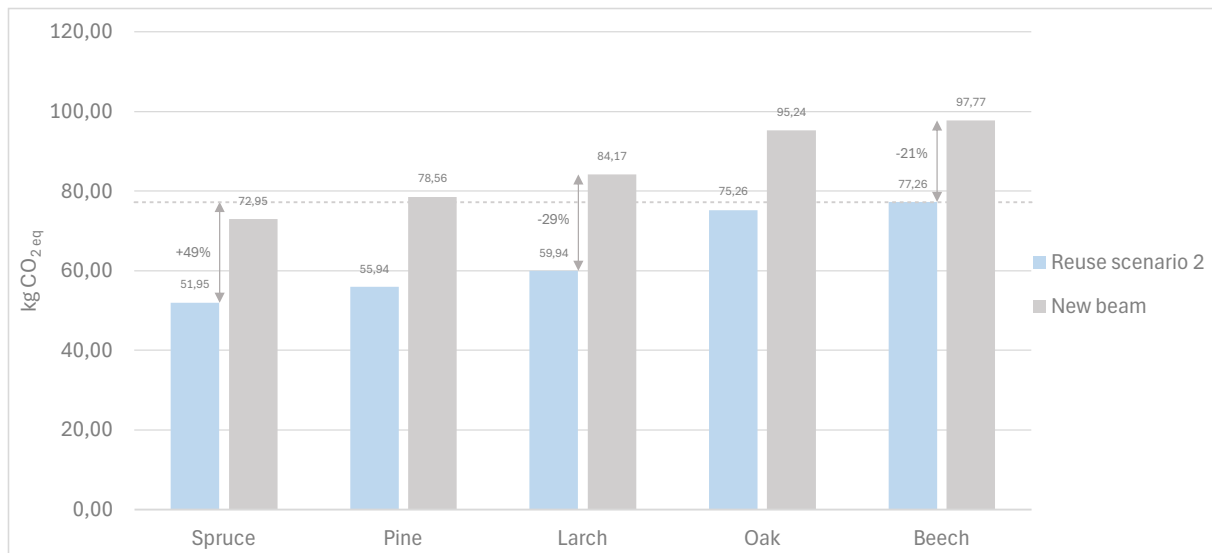


Figure 24. Fossil carbon emissions associated with the reuse stage for the selected wood species

For all species, reuse results in lower fossil carbon emissions than primary production. The relative reduction is approximately 29% for the softwood species and around 21% for oak and beech. This smaller relative reduction for hardwoods is linked to their higher initial production impacts. The same density-related trend observed in the production stage remains visible for the reuse processes, with beech showing an approximately 48% higher impact than spruce.

1.2.3 End-of-life impact

Figure 25 shows the fossil carbon emissions associated with end-of-life processes (C1–C4).

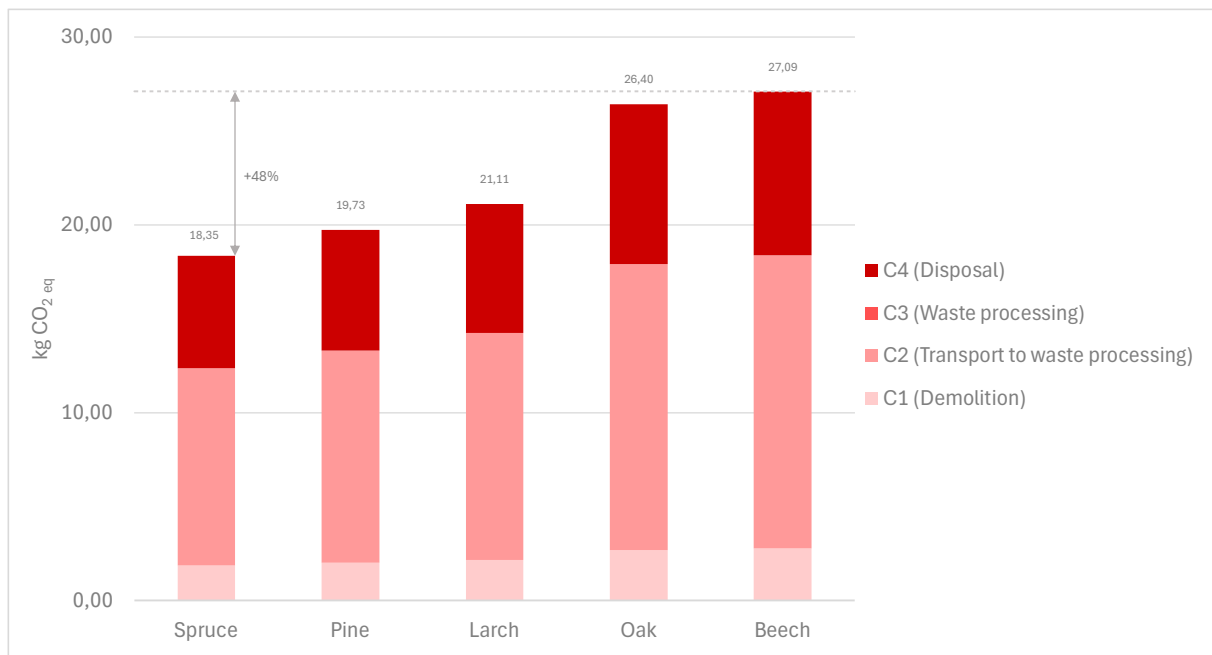


Figure 25. Fossil carbon emissions associated with end-of-life processes (C1–C4) for the selected wood species

The relatively large contribution of transport (C2) and disposal (C4) is mainly linked to the assumption that 100% of the timber is incinerated at end-of-life. Compared to the standard TOTEM scenario, where only part of the material is incinerated, a larger share of the material is therefore assigned to the incineration pathway, which involves both longer transport distances and higher disposal impacts.

1.3 Biogenic carbon emissions

Figure 26 shows the potential climate benefit associated with biogenic carbon uptake for the five selected wood species. Since carbon uptake is represented as a negative emission, larger negative values correspond to a larger potential climate benefit.



Figure 26. Biogenic carbon uptake for the selected wood species

The differences between species are influenced by both density and carbon fraction. Although larch has a higher density than pine, pine shows a slightly larger biogenic carbon uptake due to its higher carbon fraction. Oak and beech show the largest uptake values, resulting in approximately 40% larger climate benefits compared to spruce.

1.4 Comparison of allocation methods – Growth approach



Figure 27. Comparison of allocation methods for spruce under the growth approach

Figure 27 compares the five allocation methods for spruce under the baseline scenario. In the figures, each bar represents the total climate change impact of a life cycle, subdivided into fossil and biogenic carbon contributions. The number in brackets indicates the year within the 100-year assessment period at which the emission or removal is inventoried, while LC 1 and LC 2 refer to the first and second life cycle respectively. The figure shows how the allocation of biogenic carbon uptake and release between LC 1 and LC 2 influences the total climate change impact when assessed using dynamic LCA. Since dynamic characterization factors decrease over time, the timing of emissions strongly affects the final result.

Methods G1 and G2 both allocate the full carbon uptake credit to LC 1, resulting in strongly negative impacts for the first life cycle. In G1, the release is also assigned to LC 1 at year 100, where it is heavily discounted by the DCF, while LC 2 only contains reuse and end-of-life processes resulting in small positive impacts. G2 transfers the release to LC 2 where it physically occurs, slightly reducing the negative impact of LC 1. Since the release at year 100 remains heavily discounted in LC 2, the difference between both methods is relatively limited.

Method G3 reverses the allocation logic of G1 by assigning the carbon release burden to LC 1 while transferring the full uptake credit to LC 2. Since LC 1 carries the release without any offsetting sequestration credit, it results in a positive climate change impact. In contrast, LC 2 receives the full uptake credit at year 0 of its life cycle while its release at year 100 is heavily discounted by the DCF, resulting in the most negative impact of all growth-based methods.

Method G4 distributes both carbon uptake and release equally between both life cycles. Since uptake is always credited before release occurs, both life cycles result in net negative impacts, though less pronounced than for methods where the full credit is assigned to a single life cycle.

Method G5 assigns a complete and independent uptake-release pair to each life cycle. In LC 1, uptake is credited at year 0 while release occurs at year 50, meaning the release is weighted more heavily by the DCF than in G1 where release occurs at year 100. This results in a less negative impact for LC 1 compared to G1. In LC 2, uptake is credited at year 50 while release occurs at year 100 and is therefore heavily discounted, resulting in a net negative impact.

The corresponding results for pine, larch, oak, and beech are included in Appendix F and discussed in the following section.

1.5 Comparison of species – Growth approach

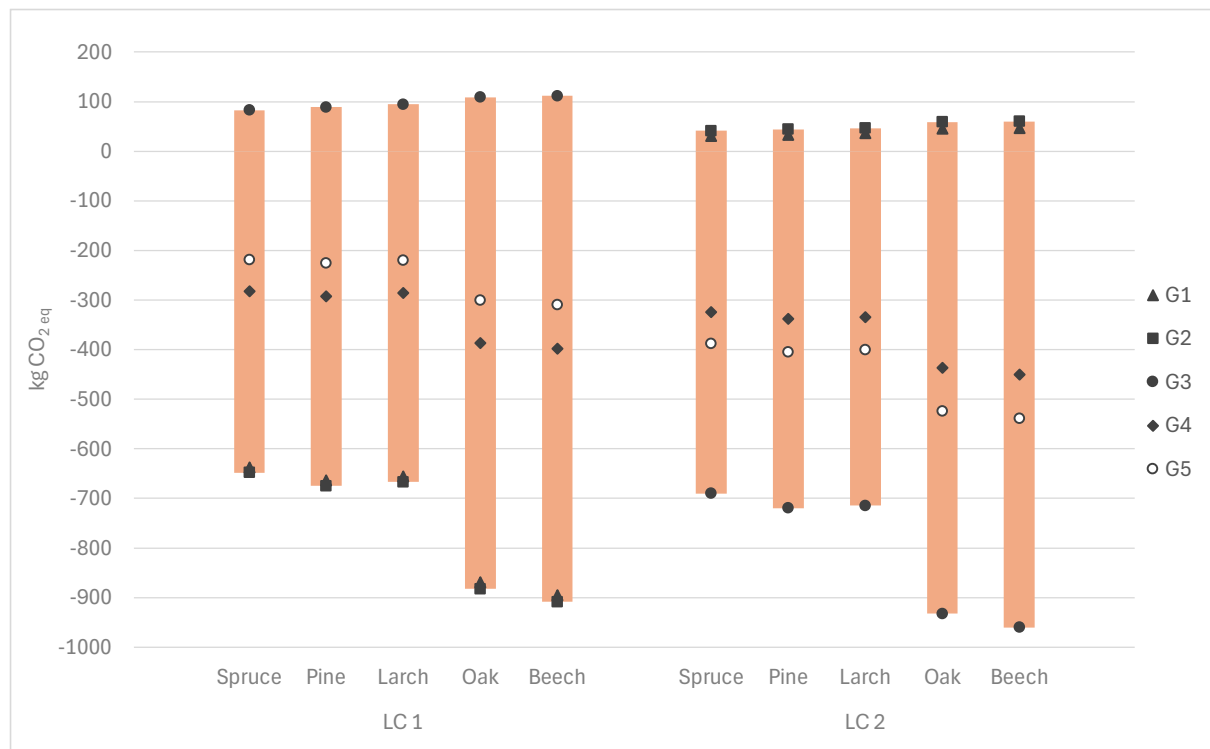


Figure 28. Comparison of allocation methods across wood species under the growth approach

The outcomes show that, although the absolute impacts differ between species, the variation caused by the allocation methods is substantially larger than the variation between wood species.

The trends discussed in Sections 1.2 and 1.3 are clearly visible in the results. For life cycles receiving the biogenic carbon credit, species with larger biogenic carbon uptake result in lower climate change impacts. In contrast, for life cycles without this credit, the impact is mainly driven by fossil emissions and therefore increases with density.

This effect can be observed for larch. Due to its higher density, larch shows higher impacts than spruce and pine for life cycles without biogenic carbon credit. However, when carbon uptake is allocated, its impact does not become lower than spruce or pine, as its lower carbon fraction results in a smaller biogenic carbon uptake.

The relative behaviour of the allocation methods remains highly consistent across all species, confirming that the conclusions drawn for spruce in section 1.4 apply broadly regardless of wood species. The results therefore indicate that the modelling approach used to allocate biogenic carbon between life cycles has a substantially larger influence on the climate change impact than the choice of wood species itself.

1.6 Comparison of allocation methods – Regrowth approach

In the growth approach, biogenic carbon uptake is fully credited at the beginning of the assessment period. Conversely, the regrowth approach distributes carbon uptake over time, meaning that sequestration occurring later in the time horizon contributes less to the overall climate change impact due to the use of dynamic characterisation factors. Figure 29 compares

the total climate benefit associated with biogenic carbon uptake under the growth and regrowth approaches for all selected wood species.

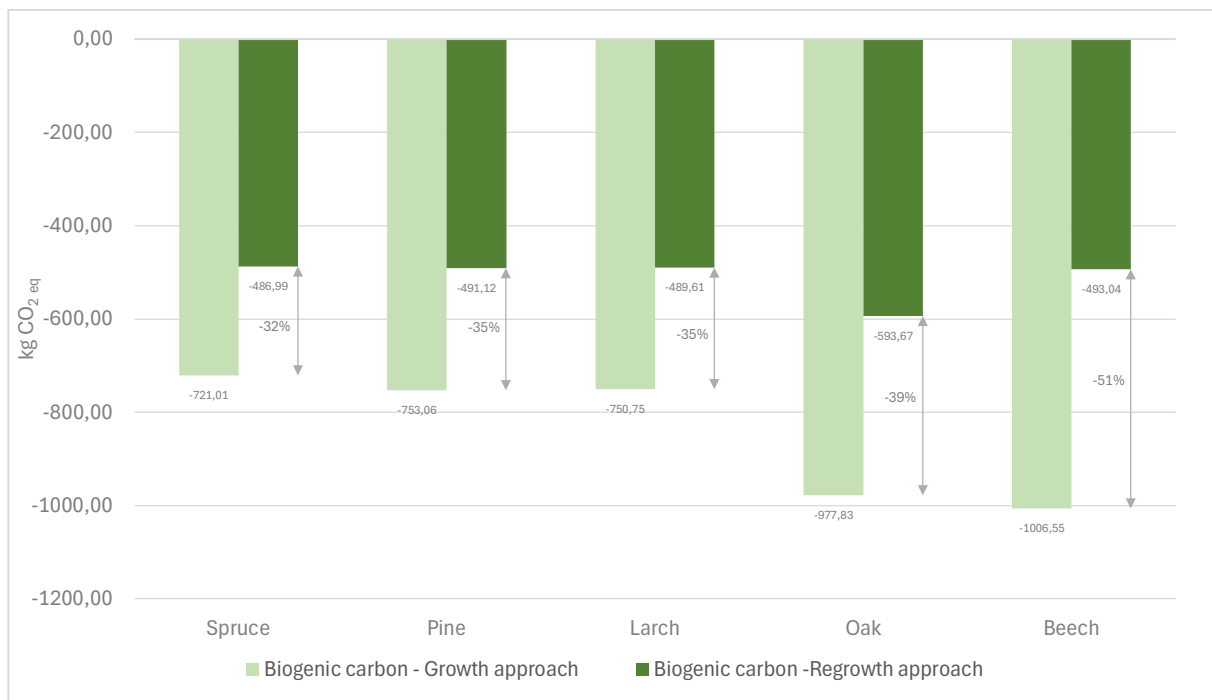


Figure 29. Comparison of biogenic carbon emissions under the growth and regrowth approaches for the selected wood species

In the growth approach, the difference between spruce and beech amounts to approximately 40%, mainly because beech has a higher density and therefore contains more biogenic carbon (section 1.3). Under the regrowth approach, this difference becomes much smaller. Spruce and beech show almost identical credits, despite the larger carbon content of beech.

This is caused by the difference in rotation period. Spruce has a rotation period of 65 years, while beech has a rotation period of 110 years. As a result, a larger share of the carbon uptake for beech occurs later in the time horizon, or partly outside the 100-year assessment period. The additional carbon stored in beech is therefore partly offset by the later timing of sequestration.

The same effect can be observed across the other species. Pine and larch both have a rotation period of 70 years and show an identical reduction compared to the growth approach. Oak, with a rotation period of 80 years, shows a larger reduction than the softwood species, but still remains more negative than beech because its rotation period is shorter. These results therefore demonstrate that under the regrowth approach, rotation period becomes equally or more influential than density in determining the total sequestration credit.

Figure 30 shows how this reduced sequestration credit influences the climate change impact across the three regrowth-based allocation methods for spruce. The corresponding results for the other wood species are included in Appendix F and discussed in section 1.7.

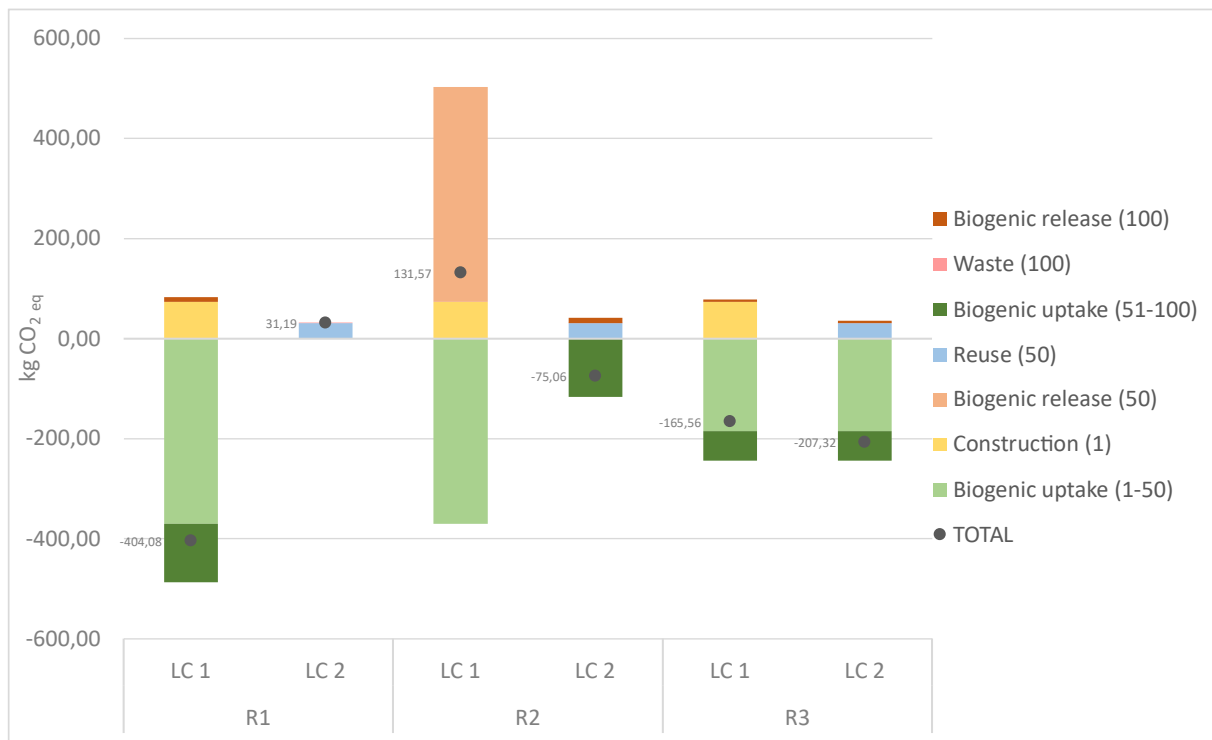


Figure 30. Comparison of allocation methods for spruce under the regrowth approach

Compared to the growth approach, the climate change impacts are less negative for all allocation methods, as the sequestration credit is distributed over time instead of being fully credited at the start of the assessment period.

Method R1 allocates all carbon uptake and release to the first life cycle, following the same logic as G1. However, the reduced sequestration credit results in a less negative impact for LC 1 compared to G1. LC 2 only contains reuse and end-of-life processes, resulting in small positive impacts.

Method R2 credits each life cycle with the carbon uptake occurring within its own timeframe, while each life cycle bears a full independent release event at its end. For LC 1, only the sequestration occurring during the first 50 years is credited, while the full carbon release at year 50 is assigned. Since this sequestration is insufficient to offset the release, LC 1 results in a positive climate change impact. In contrast, LC 2 receives the remaining sequestration credit between years 50 and 100, while its release at year 100 is heavily discounted by the DCF, resulting in a net negative impact.

Method R3 distributes both carbon uptake and release equally between both life cycles, following the same logic as G4. Since each life cycle receives half the sequestration credit while bearing half the release burden, and since uptake always precedes release, both life cycles result in net negative impacts. Compared to R1 and R2, the distribution between both life cycles is therefore more balanced.

1.7 Comparison of species – Regrowth approach

Figure 31 compares the three allocation methods for all selected wood species under the regrowth approach. Similar to the growth approach, the variation caused by the allocation methods remains substantially larger than the variation between wood species.

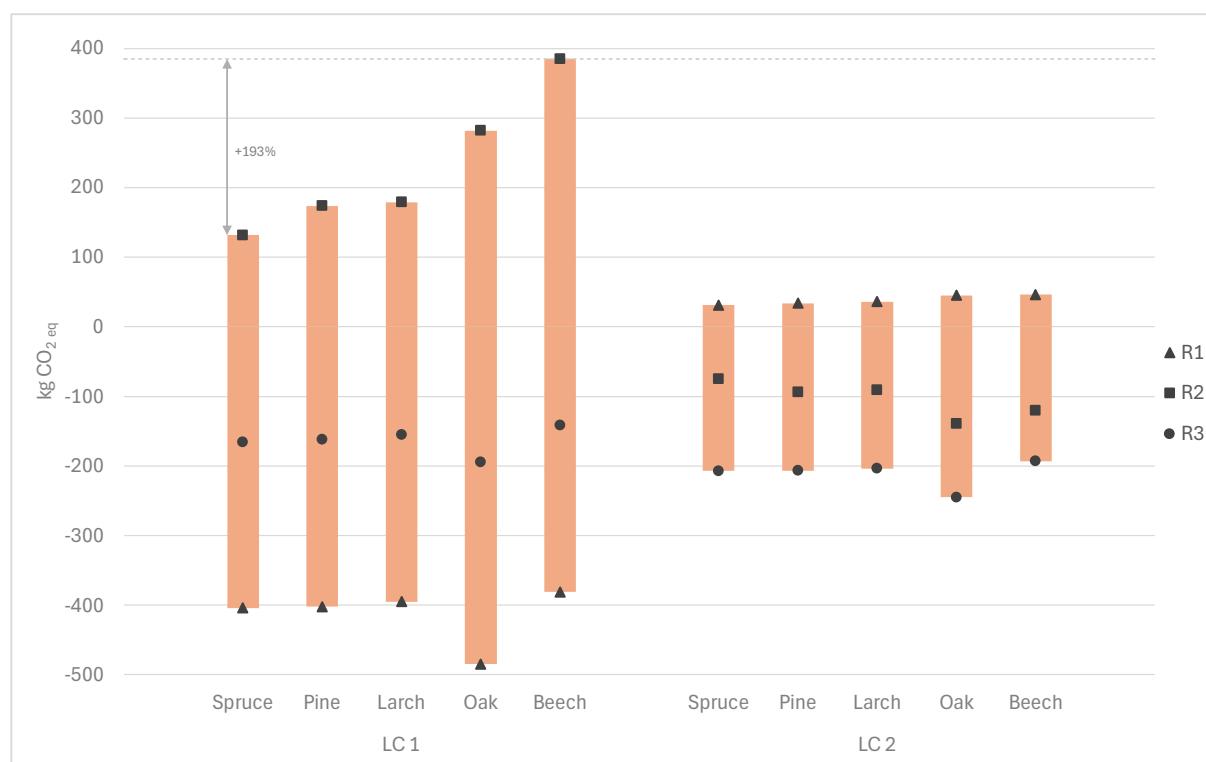


Figure 31. Comparison of allocation methods across wood species under the regrowth approach

The influence of the rotation period is most clearly visible for allocation method R2. In this method, only the carbon uptake occurring during the first 50 years is credited to the first life cycle, while the full biogenic carbon release at year 50 is still allocated to it. As a result, the climate change impact of LC 1 increases strongly from spruce to beech.

Two effects contribute to this increase. Firstly, species with higher density and carbon content result in larger biogenic carbon release at year 50. Secondly, longer rotation periods reduce the amount of carbon uptake occurring during the first life cycle. These effects reinforce each other, resulting in the highest climate change impact for beech in LC 1.

For LC 2, the variation between species becomes smaller. Since the remaining uptake after year 50 is allocated to the second life cycle, species with larger total biogenic carbon storage retain a larger sequestration credit during this phase. This is particularly visible for beech, which shows one of the lowest impacts for LC 2 despite having the highest impact for LC 1 in method R2.

Methods R1 and R3 show more straightforward species-related trends. The relative behaviour of both methods remains consistent across species, confirming the conclusions drawn in section 1.6.

1.8 Comparison of growth and regrowth approach

Figure 32 compares the results obtained under the growth and regrowth approaches for all wood species and allocation methods.

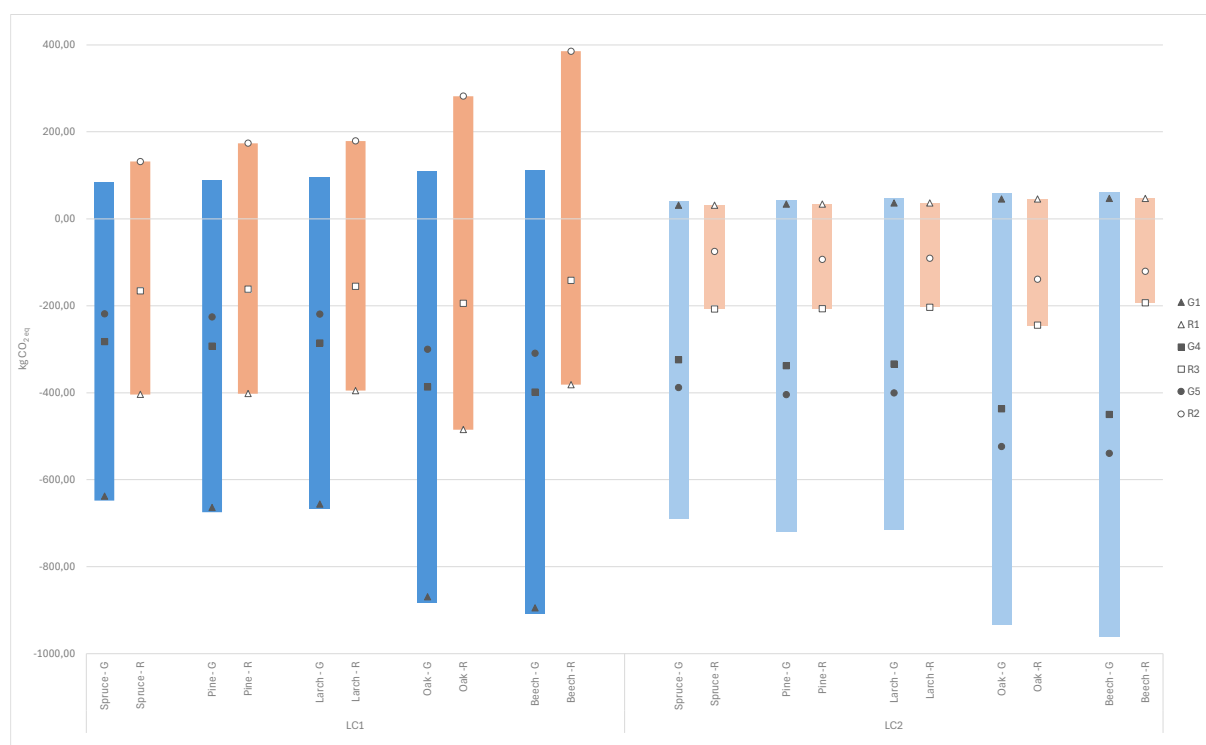


Figure 32. Comparison of allocation methods under the growth and regrowth approaches

Three corresponding sets of allocation methods can be identified: G1–R1, G4–R3, and G5–R2. Each pair follows a similar allocation logic but differs in the modelling of biogenic carbon uptake.

The comparison between G1 and R1 shows the direct influence of the uptake modelling approach. Both methods allocate the biogenic carbon uptake and release to LC 1, while LC 2 only includes reuse and waste processes. As a result, the differences between both methods are entirely caused by the reduced sequestration credit in the regrowth approach. This leads to substantially higher impacts for LC 1 in R1 compared to G1, while LC 2 remains identical.

A similar trend can be observed for G4 and R3, where biogenic carbon uptake and release are shared equally between both life cycles. Because the same allocation logic is applied, the higher impacts in R3 again result from the reduced sequestration credit in the regrowth approach. The distribution between both life cycles remains relatively balanced for both methods.

The largest differences can be observed between G5 and R2. Both methods consider the transfer of biogenic carbon between life cycles, meaning that uptake is linked to the life cycle in which it occurs. Under the growth approach, the full uptake is immediately credited, resulting in strongly negative impacts. In contrast, the regrowth approach only credits the uptake occurring during the considered life cycle. This leads to substantially higher impacts for LC 1 in R2, especially for species with longer rotation periods such as oak and beech.

1.9 Conclusion

The results show that fossil carbon emissions increase proportionally with density, while the total climate change impact is primarily governed by biogenic carbon flows. Although species-specific properties such as density and rotation period influence the magnitude of impacts, the choice of allocation method and biogenic carbon modelling approach ultimately governs the final result.

Growth-based methods consistently result in lower impacts due to immediate carbon crediting, while regrowth-based methods produce more conservative results. Both strongly negative and positive impacts are possible for the same timber element depending on the selected method, with positive impacts occurring mainly when large biogenic carbon releases are allocated to a life cycle without an equivalent sequestration credit.

2. Density – Sensitivity analysis

2.1 Introduction

Chapter 1 already demonstrated that density contributes to the differences in climate change impact observed between wood species. Density directly affects the material mass of the beam, so it influences both fossil carbon emissions and biogenic carbon storage. This chapter therefore evaluates how variations in density within each species influence the LCA results.

The minimum, median, and maximum density values introduced in section 3.2.1 of Part 2 (Methodology) are applied for each selected wood species. All other baseline assumptions remain unchanged, including the reuse scenario, service life, rotation period, and allocation methods.

The chapter first evaluates the influence of density on fossil carbon emissions and biogenic carbon emissions separately. Afterwards, the influence of density on the distribution of impacts between life cycles is assessed for selected allocation methods.

Figure 33 shows that spruce and pine have relatively similar density ranges, while larch consistently shows higher densities among the softwoods. Oak and beech show the highest density values overall.

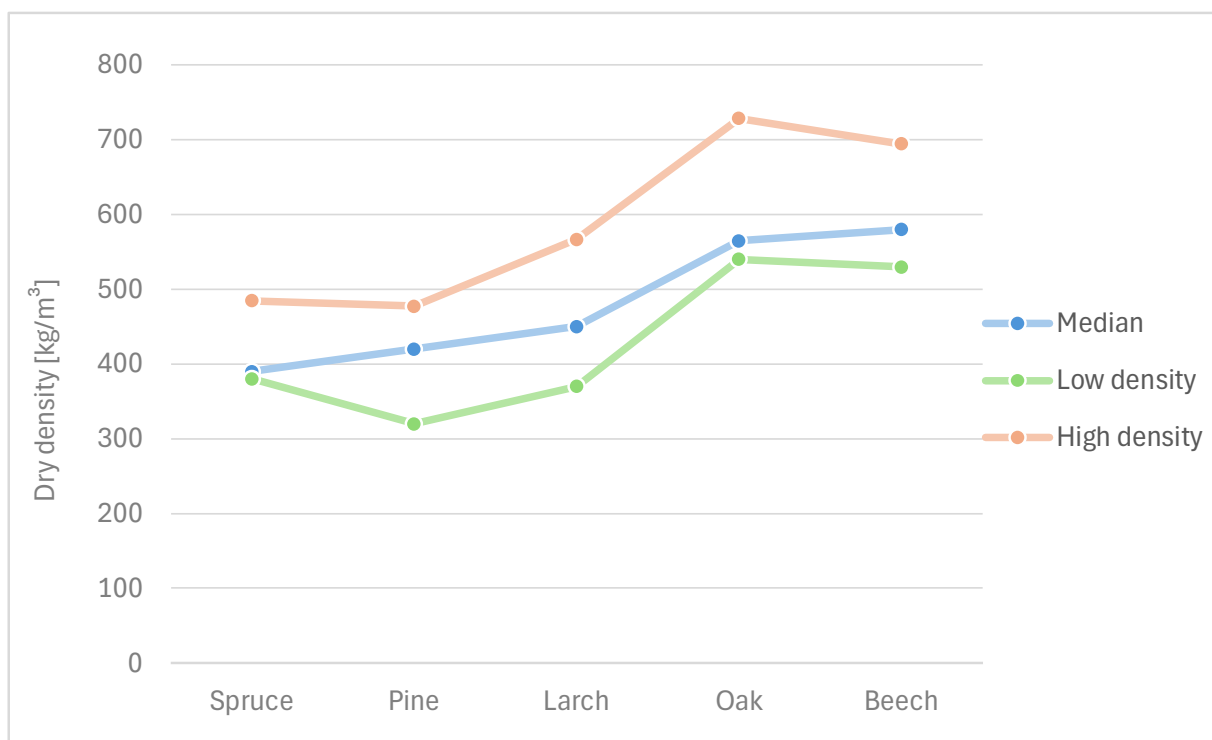


Figure 33. Minimum, median, and maximum density values for the selected wood species

2.2 Impact on fossil carbon emissions

Chapter 1 displayed that fossil carbon emissions increase consistently with density. This section evaluates how variations in density within each wood species influence the fossil carbon emissions associated with new and reused structural timber beams. Figure 34 shows the influence of density variation on the fossil carbon emissions of new and reused structural timber beams.

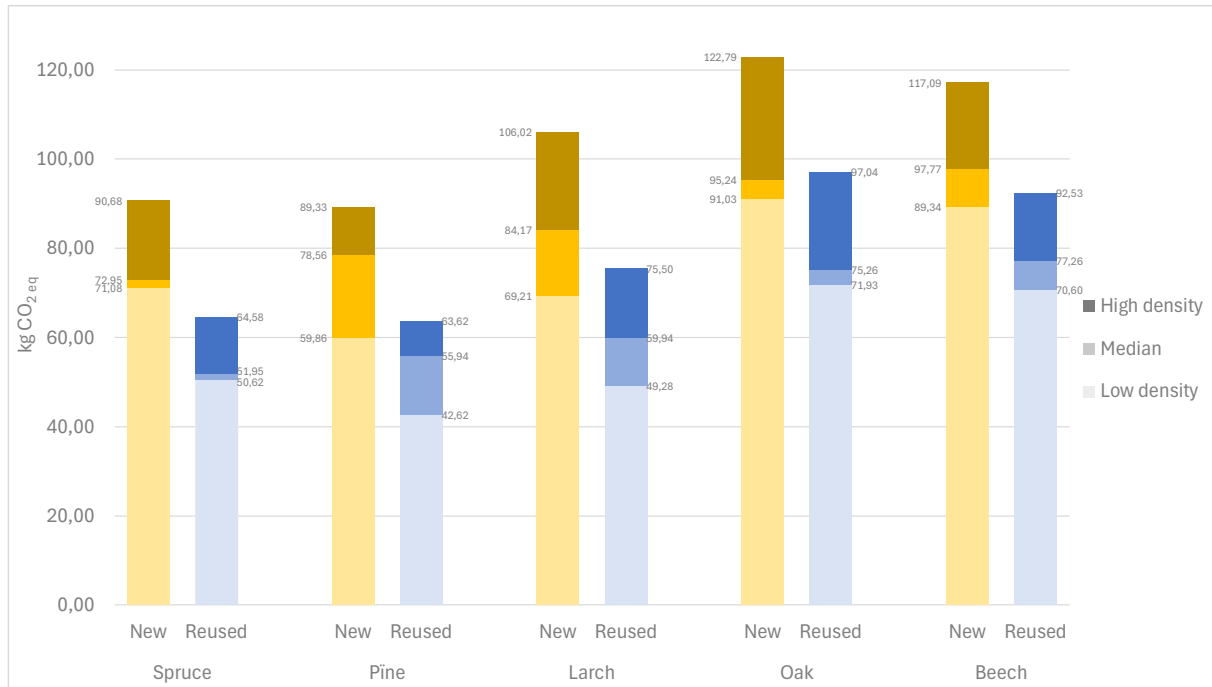


Figure 34. Influence of density variation on the fossil carbon emissions of new and reused structural timber beams

The results confirm that fossil carbon emissions scale proportionally with density, as the assessed impacts are directly related to the material mass of the beam. The trends discussed in the introduction to this chapter are also clearly visible in the results. Larch consistently shows the highest impacts among the softwoods, with the maximum density scenario even exceeding the median values of oak and beech. Similarly, the median density value of larch approaches the minimum values of the hardwood species.

The variation between density scenarios also differs substantially between species. Pine shows a relatively large increase between the minimum and median density values, whereas oak demonstrates a more limited increase between the minimum and median scenarios but a much larger increase towards the maximum density value. This shows that not only the absolute density values, but also the selected density range within a species can significantly influence the calculated fossil carbon emissions.

The comparison between new and reused beams further highlights the importance of density assumptions in comparative assessments. Although reused beams consistently show lower fossil carbon emissions within the same density scenario, for all species except spruce a high-density reused beam results in higher fossil carbon emissions than a low-density new beam of the same species.

The same proportional relationship between density and fossil carbon emissions is also observed for the end-of-life processes, as these impacts are likewise driven by material mass. The corresponding figure is included in the Appendix G.

2.3 Impact on biogenic carbon emissions

Chapter 1 illustrated that biogenic carbon emissions dominate the overall climate change impact of the assessed timber systems. This section therefore evaluates the influence of density variation on the biogenic carbon emissions under both the growth and regrowth approaches. Figure 35 shows the biogenic carbon emissions for the minimum, median, and maximum density values of the selected wood species.

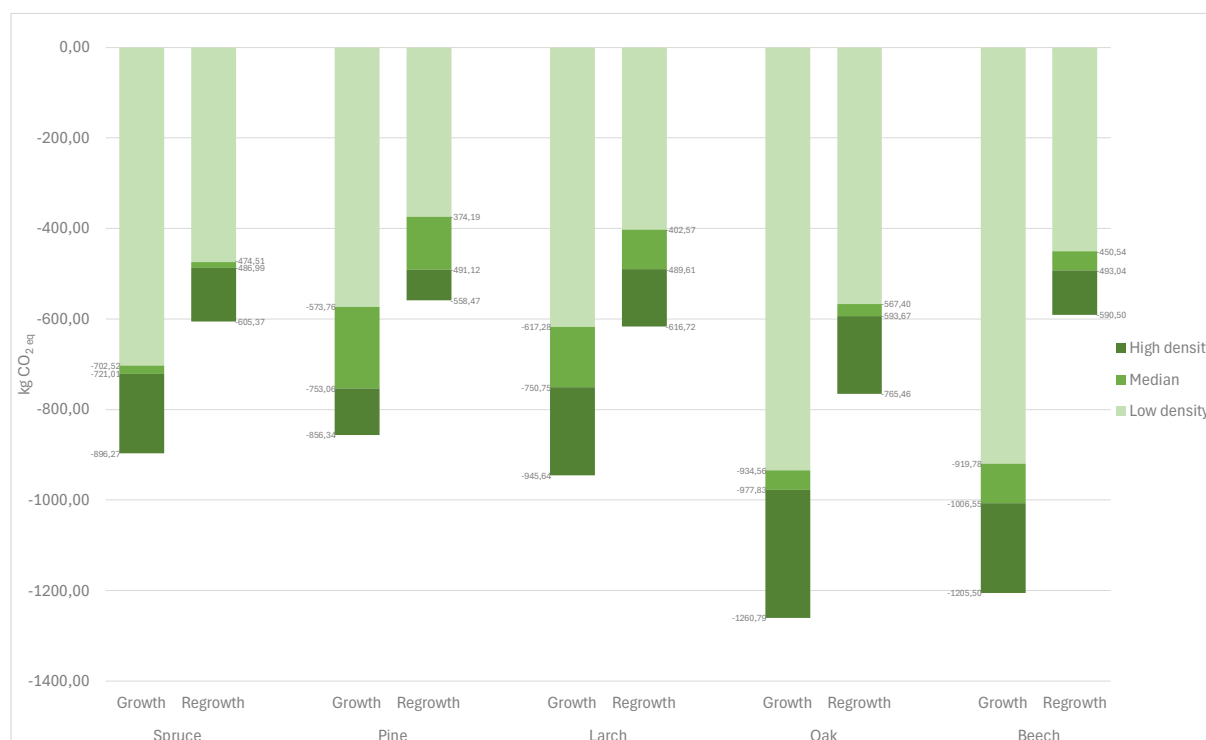


Figure 35. Biogenic carbon emissions for different density values under the growth and regrowth approaches

Compared to the fossil carbon emissions discussed in Section 2.2, the influence of density on biogenic carbon emissions is substantially larger in absolute terms. While density affects fossil emissions proportionally through material mass, it directly determines the total amount of stored biogenic carbon, which as shown in Chapter 1 dominates the overall climate change impact.

The interaction between density and carbon fraction remains visible — in the median scenario, larch shows a slightly lower biogenic carbon uptake than pine despite its higher density, due to its lower carbon fraction. However, under the minimum and maximum density scenarios, larch results in a larger sequestration credit than pine, demonstrating that density variation can offset the effect of a lower carbon fraction.

The results further show that the influence of the modelling approach remains larger than the variation caused by density itself. For all assessed species, even the maximum density scenario under the regrowth approach results in a smaller climate benefit than the minimum density

scenario under the growth approach, demonstrating the dominant influence of the selected biogenic carbon modelling approach.

2.4 Influence of density on allocation method G1

As stated in the introduction, the influence of density on the distribution of impacts between life cycles is evaluated for three allocation methods with contrasting allocation logics: full allocation to one life cycle (G1), independent biogenic carbon cycles (G5), and time-based distribution (R2). This section focuses on allocation method G1, while the following section evaluates methods G5 and R2. Figure 36 shows the influence of density variation on allocation method G1.

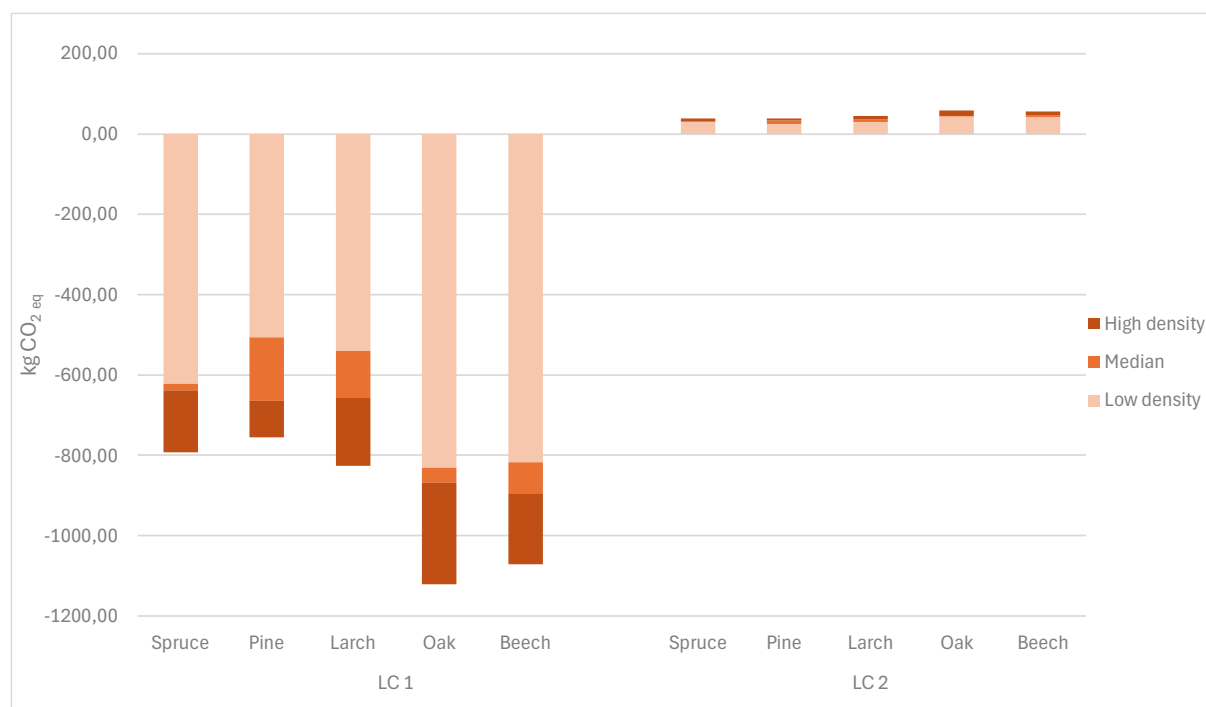


Figure 36. Impact of density variation for allocation method G1

The influence of density is mainly concentrated in the first life cycle. Since allocation method G1 assigns both biogenic carbon uptake and release to LC 1, the climate change impact of the first life cycle is dominated by the sequestration credit. Higher density values therefore result in substantially more negative impacts due to the larger amount of stored biogenic carbon.

Conversely, the second life cycle only includes reuse and end-of-life processes, and since only fossil carbon emissions remain allocated to LC 2, higher density values lead to slightly higher climate change impacts — the opposite effect to LC 1.

The remaining allocation methods, included in Appendix G, show related but distinct patterns. Method G2 shows similar trends to G1 for LC 1, but the density effect becomes visible in LC 2 as well due to the transferred carbon release. Method G3 shows the opposite pattern to G1, with density effects concentrated in LC 2 through the transferred sequestration credit. Methods G4 and R3 show balanced density effects across both life cycles, while R1 follows the same pattern as G1.

2.5 Influence of density on allocation methods G5 and R2

Allocation methods G5 and R2 differ from G1 in the way biogenic carbon uptake and release are distributed between both life cycles. Instead of allocating the full sequestration credit to a single life cycle, both methods separate the carbon flows between LC 1 and LC 2. Figure 37 shows the influence of density variation on allocation method G5.

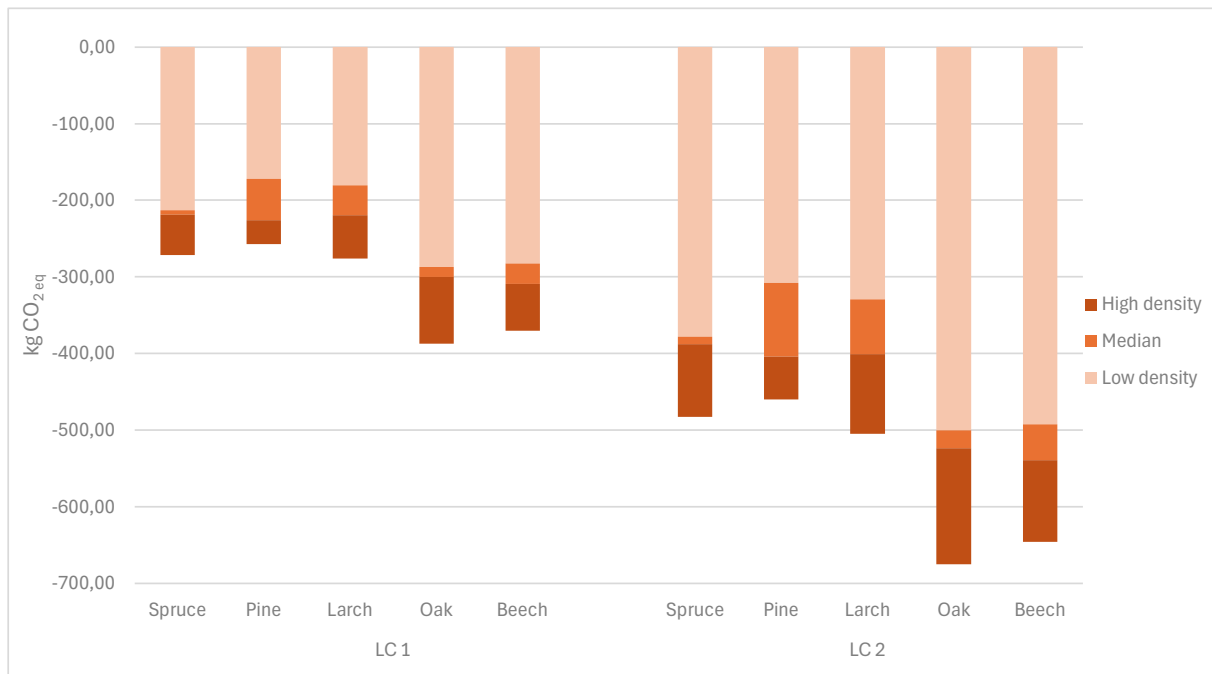


Figure 37. Impact of density variation for allocation method G5

Compared to G1, the differences between density scenarios become smaller for the first life cycle. Although higher density values still result in larger biogenic carbon uptake, the earlier carbon release occurring in year 50 offsets a substantial part of this sequestration credit. Subsequently, the net differences between the minimum and maximum density scenarios are reduced.

In LC 1, uptake is credited at year 0 while release occurs at year 50. Compared to G1, where release occurs at year 100, the earlier release is weighted more heavily by the DCF, reducing the net climate benefit. Higher density values therefore result in less strongly negative impacts than in G1.

In LC 2, uptake is credited at year 50 while release occurs at year 100. Since the release is more strongly discounted by the DCF, the balance between uptake and release is more favourable than in LC 1. Higher density values therefore lead to larger net climate benefits in LC 2, particularly visible for oak and beech.

In contrast to G5, allocation method R2 credits each life cycle only with the sequestration occurring within its own timeframe, while each life cycle bears a full independent release event. Figure 38 shows the influence of density variation on allocation method R2.

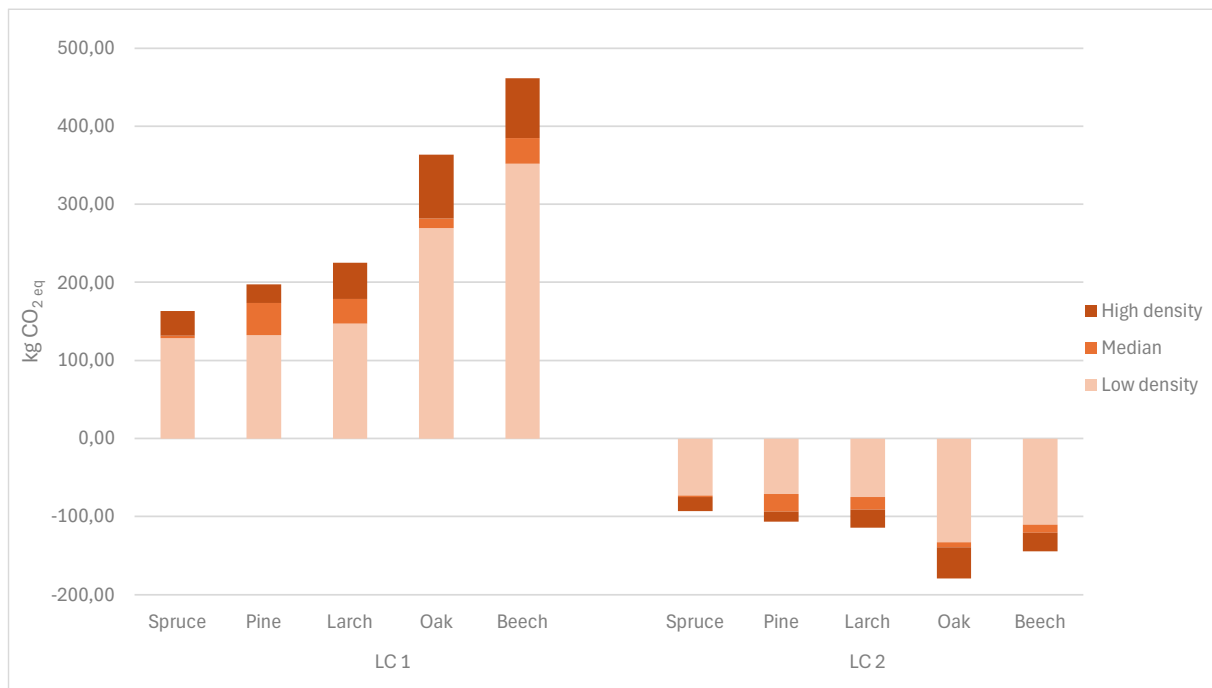


Figure 38. Impact of density variation for allocation method R2

In LC 1, only the sequestration occurring during the first 50 years is credited while the full release at year 50 is assigned. Since this sequestration is insufficient to offset the release, LC 1 shows positive climate change impacts for all species. Higher density values further increase these impacts as both the release and the limited sequestration credit grow proportionally, but the release dominates.

In LC 2, the remaining sequestration between years 50 and 100 is credited while the release at year 100 is heavily discounted by the DCF. Higher density values therefore result in larger sequestration credits and lower climate change impacts.

2.6 Conclusion

The results confirm that the influence of density on fossil carbon emissions is direct and proportional, as impacts scale with the material mass of the beam. Density variation can therefore partly outweigh the differences between reused and new beams, resulting in overlap between high-density reuse scenarios and low-density new production scenarios.

In contrast, the influence of density on biogenic carbon emissions is substantially larger, since density directly determines the amount of stored biogenic carbon and therefore the magnitude of both carbon uptake and release. Nevertheless, the differences caused by the growth and regrowth approaches remain larger than the variation caused by density itself, demonstrating the dominant influence of the selected biogenic carbon modelling approach.

The influence of density on the distribution of impacts between life cycles depends strongly on the selected allocation method. When no biogenic carbon credit is allocated to a life cycle, higher density leads to higher impacts through increased fossil emissions. When a sequestration credit is allocated, higher density results in lower impacts through increased carbon storage. Ultimately, the timing of carbon uptake and release determines how these density effects are distributed across consecutive life cycles.

3. Rotation period – Sensitivity analysis

3.1 Introduction

Chapter 1 already demonstrated that rotation period significantly influences the climate change impact in the regrowth approach, as carbon sequestration occurs gradually over time. Species with longer rotation periods showed substantially lower sequestration credits because a larger share of carbon uptake occurs later in the assessed time horizon. For long rotation periods, part of the carbon uptake can even occur outside the 100-year assessment period, further reducing the sequestration credit. This chapter therefore evaluates how variations in rotation period within each wood species influence the LCA results.

The minimum, median, and maximum rotation periods introduced in section 3.2.2 of Part 2 (Methodology) are applied for each selected wood species. All other baseline assumptions remain unchanged, including the reuse scenario, density values, carbon fractions, service life of 50 years per life cycle, and allocation methods.

The chapter first evaluates the influence of rotation period on biogenic carbon sequestration in the regrowth approach. Afterwards, the influence of rotation period on the distribution of impacts between life cycles is assessed for selected allocation methods.

Figure 39 shows the minimum, median, and maximum rotation period values used for the selected wood species.

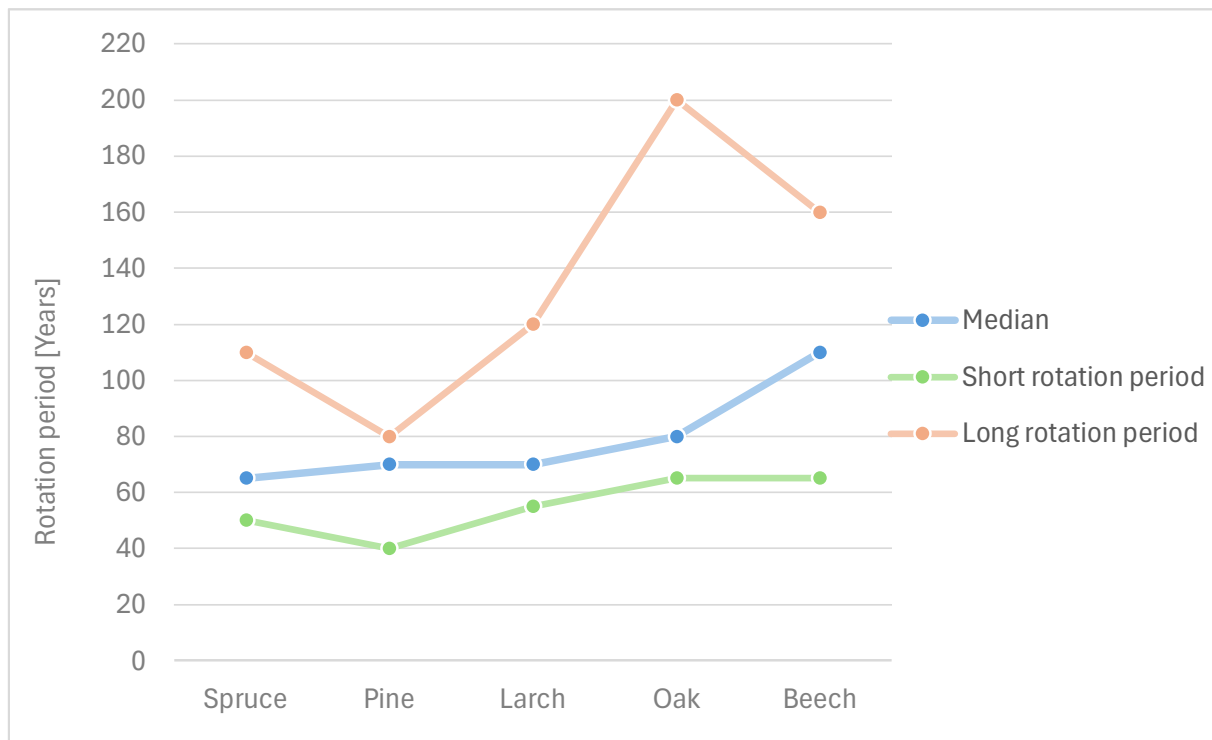


Figure 39. Minimum, median, and maximum rotation period values for the selected wood species

The variation within a species can be substantial. Oak shows the largest spread, with values ranging from 65 to 200 years, while beech ranges from 65 to 160 years. Pine shows the smallest overall range, with rotation periods between 40 and 80 years. Spruce and larch show intermediate variations, although the maximum value of larch remains noticeably higher than that of spruce and pine.

Clear differences can also be observed between species. Spruce, pine, and larch generally show shorter rotation periods, while oak and beech show substantially longer values, particularly for the maximum scenarios. Nevertheless, an overlap between species remains visible. For example, the minimum rotation periods of oak and beech are similar to the median rotation period of spruce, while the maximum rotation period of pine remains lower than the median values of oak and beech. This demonstrates that both species selection and the choice of forestry assumptions strongly influence the applied rotation period values.

Figure 40 shows the cumulative biogenic carbon uptake over time for the selected rotation period scenarios.

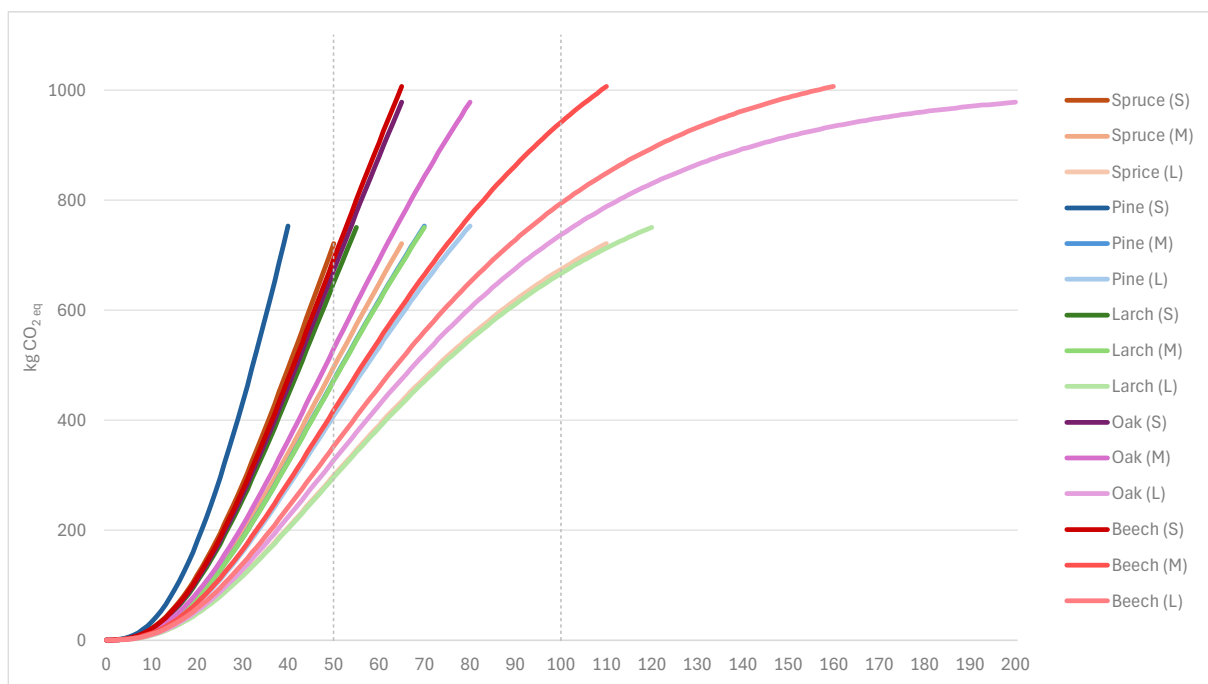


Figure 40. Biogenic carbon uptake over time for the selected wood species and rotation period scenarios

The curves illustrate how longer rotation periods delay carbon sequestration over the assessed time horizon. Species and scenarios with shorter rotation periods show a steeper increase in carbon uptake, meaning that a larger share of sequestration occurs earlier in time. In contrast, longer rotation periods distribute carbon uptake more gradually, causing part of the sequestration to occur after the first life cycle or even outside the 100-year assessment period.

This effect is particularly visible for oak and beech under the maximum rotation period scenarios. Even after 100 years, a substantial share of the total carbon uptake has not yet occurred. In contrast, species with shorter rotation periods, such as pine and spruce, reach most of their total sequestration within the assessed time horizon.

3.2 Impact on biogenic carbon emissions

Figure 41 shows the influence of the minimum, median, and maximum rotation period values on the climate change impact of biogenic carbon uptake under the regrowth approach.

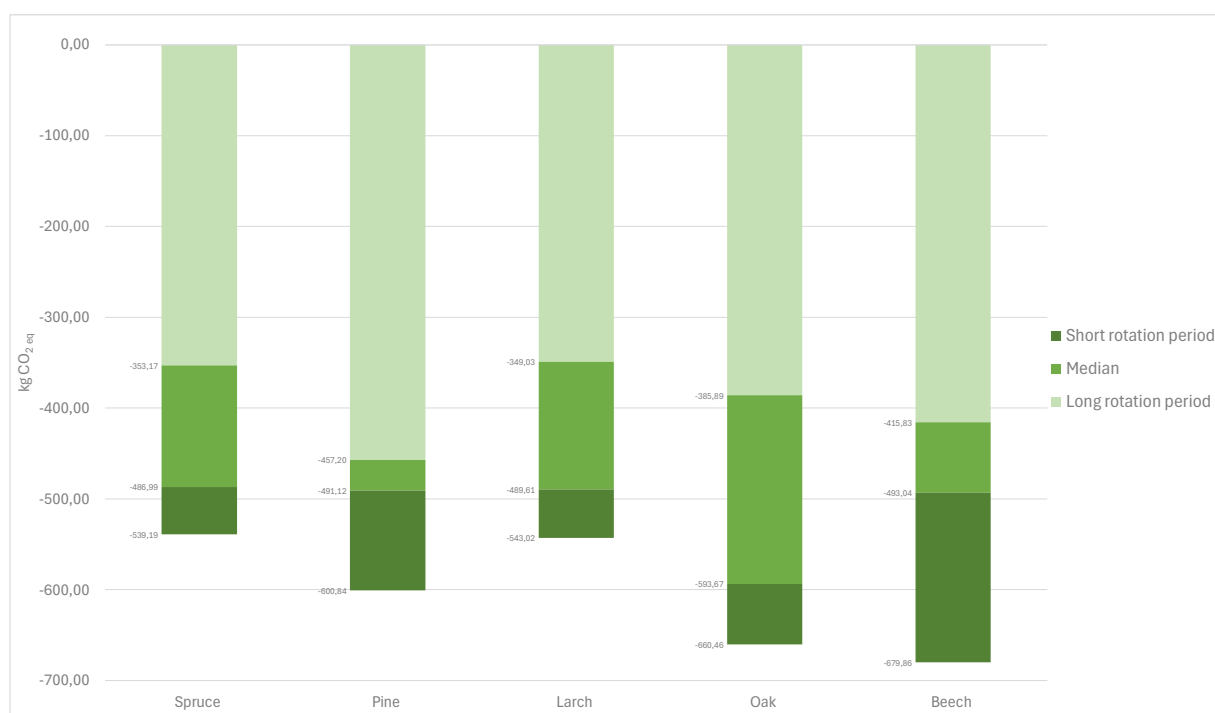


Figure 41. Influence of rotation period variation on biogenic carbon sequestration

Increasing the rotation period consistently reduces the sequestration credit, with the magnitude of this reduction depending primarily on whether the rotation period exceeds the 100-year assessment period.

The variation between rotation period scenarios is substantial across all species, though the effect differs in nature. For softwood species, the reduction in sequestration credit mainly reflects delayed uptake within the assessed period, with pine showing the smallest variation as its longest rotation period remains below 80 years. For oak and beech, the longer rotation periods additionally cause a larger share of sequestration to fall outside the 100-year time horizon entirely; For beech, this effect already occurs in the baseline scenario due to its median rotation period of 110 years.

As a result, the differences between species become substantially smaller for long rotation periods. Despite containing more biogenic carbon, oak and beech see their sequestration credit reduced towards values similar to the softwood species. Long rotation periods can therefore neutralise the carbon storage advantage associated with higher density.

3.3 Method R2

Among the assessed allocation methods, R2 shows the strongest sensitivity to rotation period variation. Carbon uptake is distributed between both life cycles according to its timing while the biogenic carbon releases remain allocated to LC 1 and LC 2 at years 50 and 100 respectively. Consequently, the rotation period directly determines how much sequestration is available to

offset the emissions within each life cycle. Figure 42 shows the influence of rotation period variation on allocation method R2.

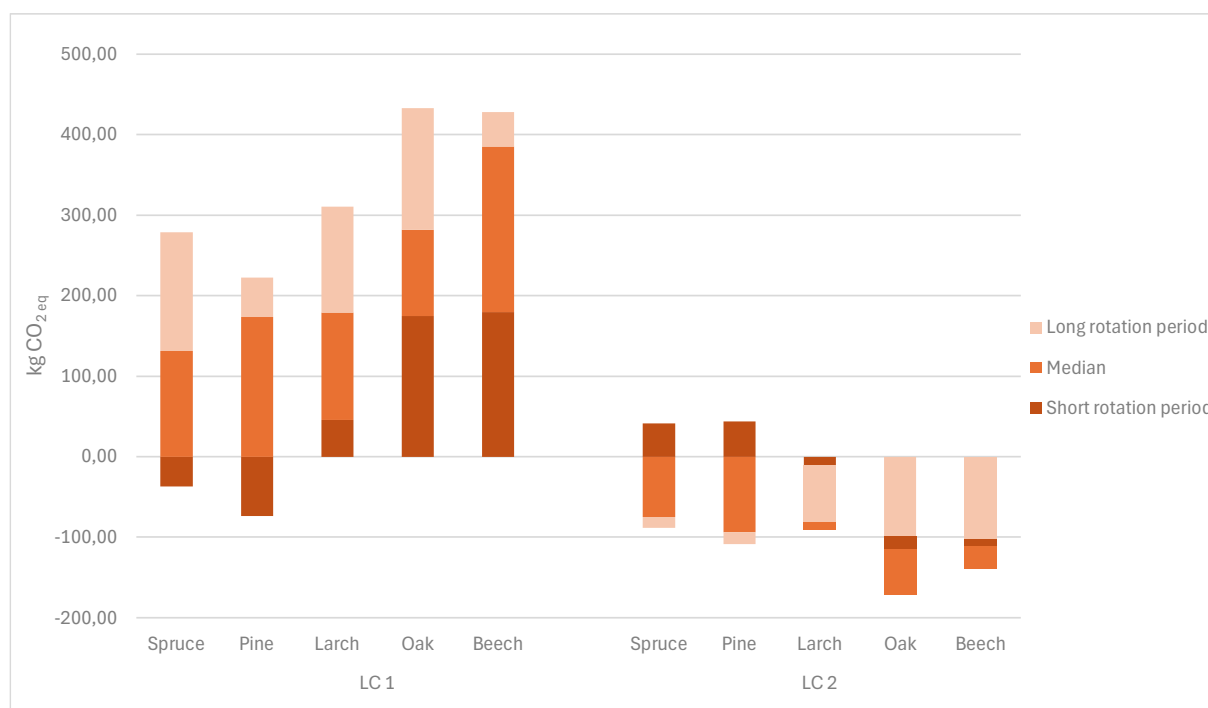


Figure 42. Impact of rotation period variation for allocation method R2

For short rotation periods, a large share of the carbon uptake occurs before year 50 and is therefore allocated to the first life cycle. In these cases, the sequestration credit can offset a substantial part of the biogenic carbon release occurring at the end of LC 1. This can be observed most clearly for spruce and pine, where the minimum rotation period scenarios result in negative or only slightly positive climate change impacts for LC 1.

As the rotation period increases, a larger share of the carbon uptake shifts towards the second life cycle or beyond the 100-year assessment period. The sequestration credit allocated to LC 1 therefore decreases strongly, while the biogenic carbon release at year 50 remains unchanged. This results in rapidly increasing climate change impacts for the first life cycle, with the strongest increase occurring for oak and beech.

The redistribution of carbon uptake between life cycles is also clearly visible in LC 2, where the ranking between rotation period scenarios differs between species. For spruce and pine, impacts improve consistently from short to long rotation periods, as more sequestration shifts towards LC 2 without falling outside the assessed period. For larch, the short rotation period results in the worst outcome as too little sequestration remains for LC 2, while the long rotation period causes part of the uptake to fall outside the assessment period — making the median scenario most favourable. For oak and beech, the long rotation period results in the worst outcome, as their extreme maximum rotation periods cause a substantially larger share of sequestration to fall outside the 100-year time horizon. While the short rotation period shifts too much sequestration to LC 1, the median scenario provides the most favourable balance for LC 2.

Methods R1 and R3, included in Appendix H, show more straightforward trends. In R1, the full sequestration credit is allocated to LC 1 regardless of timing, meaning that longer rotation periods

consistently reduce the sequestration credit without redistributing it between life cycles. Consequently, LC 2 remains completely unaffected by rotation period variation as no biogenic carbon is allocated to it. In R3, both uptake and release are equally distributed between life cycles, resulting in a more moderate sensitivity to rotation period variation compared to R2.

3.4 Conclusion

The results demonstrate that rotation period is a key parameter in the regrowth approach, as it directly determines the timing of biogenic carbon uptake. Longer rotation periods consistently reduce the sequestration credit, since a larger share of the carbon uptake occurs later in the assessment period or outside the 100-year time horizon.

The sensitivity analysis further shows that long rotation periods can substantially reduce the differences between wood species. Although oak and beech contain more biogenic carbon than the softwood species, a larger share of their sequestration occurs beyond the assessed period for the long rotation period scenarios. As a result, the climate change impacts converge towards similar values across species.

Among the assessed allocation methods, R2 shows the strongest sensitivity to rotation period variation. Short rotation periods concentrate carbon uptake in the first life cycle, while longer rotation periods shift sequestration towards the second life cycle or beyond the assessment period. For most species, the median rotation period provides the most favourable balance for LC 2. Short rotation periods shift too much sequestration to LC 1, while very long rotation periods cause part of the uptake to fall outside the 100-year time horizon. The results therefore demonstrate that the timing of carbon uptake can strongly influence the distribution of climate change impacts between life cycles.

As with density, the influence of rotation period ultimately depends on the selected allocation method and biogenic carbon modelling approach, with methodological choices continuing to dominate the final climate change impact.

4. Reuse scenario – Sensitivity analysis

4.1 Introduction

Reuse processes contribute a smaller share to the total climate change impact than biogenic carbon flows and allocation choices, as shown in Chapter 1. Nevertheless, the impact of reuse can vary substantially depending on transport distances, required processing steps, and the use of auxiliary materials. This chapter therefore evaluates how different reuse scenarios influence the LCA results.

The four reuse scenarios introduced in section 3.4 of Part 2 (Methodology) are assessed. These scenarios differ in transport distances, storage conditions, and the extent of required surface treatments and processing steps. Detailed process descriptions and species-specific impacts for each reuse scenario are included in Appendix D. All other baseline assumptions remain unchanged, including the density values, rotation periods, service life of 50 years per life cycle, and allocation methods.

The chapter first compares the climate change impact of the four reuse scenarios with the impact of a new structural timber beam. Afterwards, the influence of reuse scenario selection on the climate change impact of the second life cycle is assessed for selected allocation methods.

Figure 43 compares the climate change impact of reuse scenarios 1–4 with the impact of a new beam for spruce.

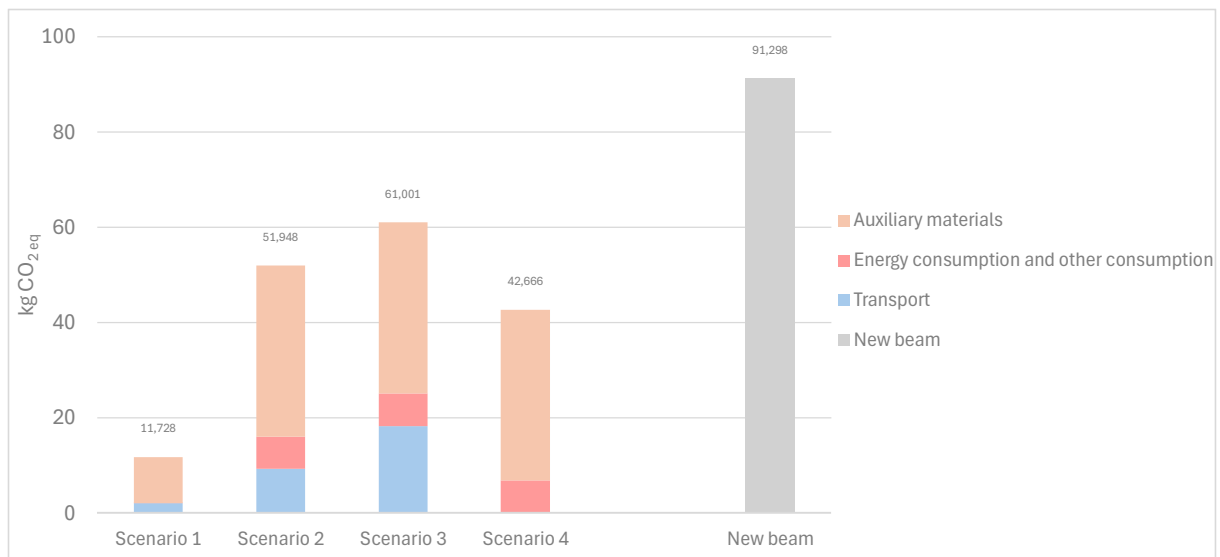


Figure 43. Climate change impact of reuse scenarios 1–4 compared to a new beam for spruce

The outcomes show that all assessed reuse scenarios result in substantially lower climate change impacts than the production of a new beam. Scenario 1 shows the lowest impact, while scenario 3 results in the highest impact due to the combination of long transport distances and additional processing requirements. Nevertheless, even the most impact-intensive reuse scenario remains clearly below the impact of new production.

The contribution analysis shows that auxiliary materials dominate the climate change impact of the reuse processes. Waterproof coverings, (fire-resistant) paint, and epoxy resin account for the largest share of the impacts in scenarios 2–4. Transport only becomes a major contributor in scenario 3, where long transport distances are assumed. Scenario 4 further demonstrates that reuse processes can still result in relatively high impacts even with limited transport when more intensive treatments or additional materials are required.

4.2 Reuse processes without carbon credit

Reuse and waste processes are consistently allocated to the second life cycle in all assessed allocation methods, as explained in Part 2 (Methodology). For allocation methods G1 and R1, this means that the second life cycle only contains reuse and waste processes. Chapter 1 showed that both methods therefore result in identical impacts for LC 2, despite the different modelling approaches for biogenic carbon uptake. As a result, the influence of the selected reuse scenario becomes highly visible in the total climate change impact of the second life cycle. Figure 44 shows the influence of reuse scenario variation for methods G1 and R1.

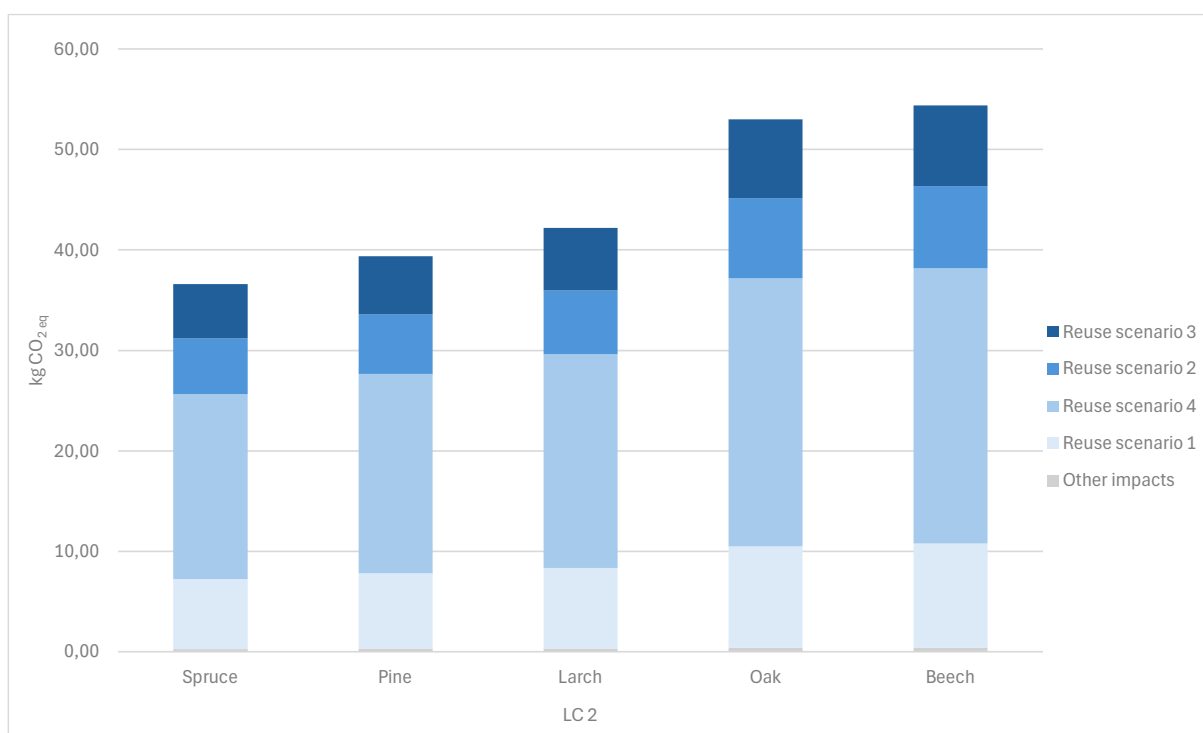


Figure 44. Impact of reuse scenario variation for allocation methods G1 and R1

The variation between reuse scenarios follows the same pattern observed in Section 4.1, with scenario 3 resulting in the highest impacts due to its more intensive reclamation operations and longer transport distances. Because methods G1 and R1 allocate no biogenic carbon credit to the second life cycle, these reuse-related processes become the dominant contributor to the total LC 2 impact. The contribution of waste processes remains small across all species and scenarios, meaning the selected reuse scenario is the primary source of variation. The differences between wood species follow a consistent density-related trend, with oak and beech showing the highest impacts due to their larger material mass.

4.3 Reuse processes with carbon credit

Figure 45 shows the influence of reuse scenario variation for allocation methods G5 and R2. In contrast to methods G1 and R1, both methods assign biogenic carbon uptake to the second life cycle. As a result, LC 2 remains net negative for all assessed species and reuse scenarios.

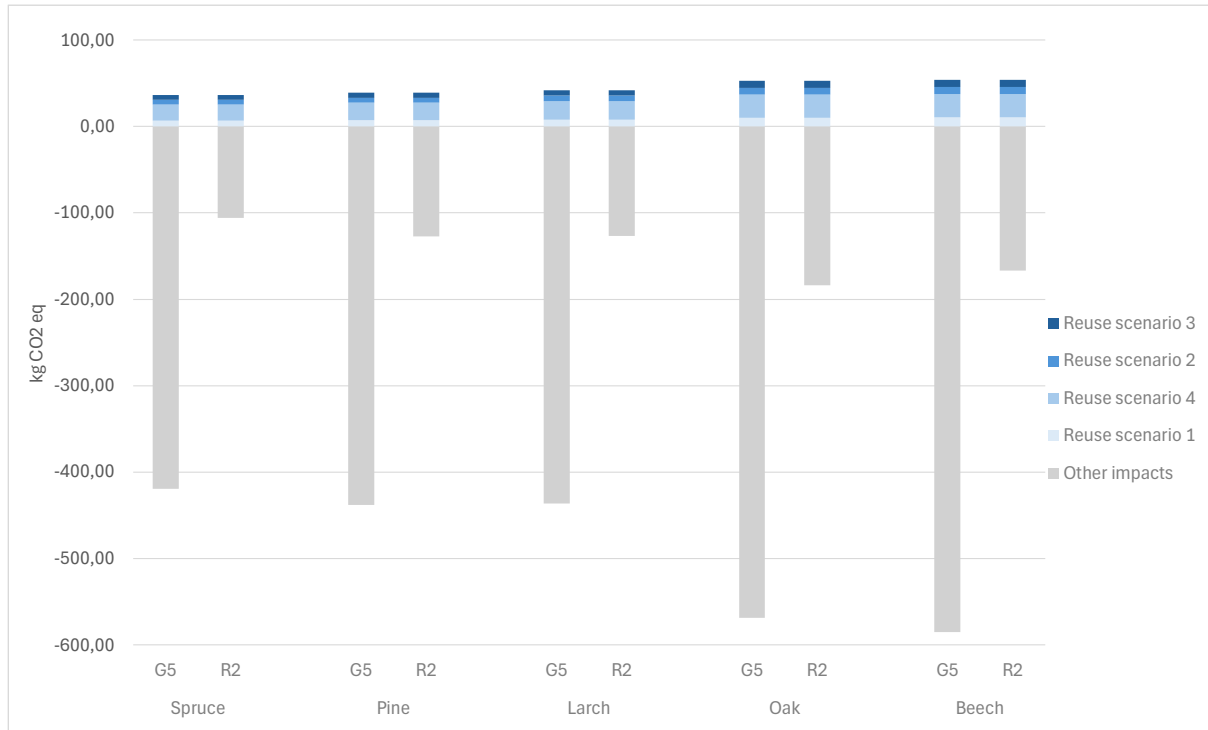


Figure 45. Impact of reuse scenario variation for allocation methods G5 and R2

The biogenic carbon flows dominate the total climate change impact to such an extent that the differences between reuse scenarios are barely visible in the results. Although the relative differences between scenarios remain consistent with those observed in section 4.1, their contribution becomes negligible once biogenic carbon uptake is assigned to LC 2.

Nevertheless, clear differences remain visible between methods G5 and R2. In G5, the full sequestration credit is assigned to LC 2 under the growth approach, strongly reducing the relative contribution of reuse processes. In R2, only the sequestration occurring during the second life cycle is credited, resulting in higher overall impacts and making the reuse scenario differences slightly more visible, though still small compared to the biogenic carbon flows.

The remaining allocation methods are included in Appendix I. In method G2, the biogenic carbon release allocated to LC 2 at year 100 is heavily discounted by the DCF, slightly reducing the relative importance of reuse processes compared to G1. Methods G4 and R3 distribute both uptake and release equally between life cycles, resulting in intermediate impacts where reuse processes are offset by the shared sequestration credit. Method G3 results in the smallest relative contribution of reuse processes, as the full sequestration credit is assigned to LC 2 without any corresponding release burden.

4.4 Conclusion

The results show that differences between reuse scenarios are mainly driven by auxiliary materials and, to a lesser extent, transport distances, with more intensive processing requirements leading to higher climate change impacts. Nevertheless, all assessed reuse scenarios remain clearly below the impact of new production.

Overall, the impact of reuse scenario selection depends strongly on the allocation of biogenic carbon flows between life cycles. For methods G1 and R1, the selected reuse scenario becomes the dominant source of variation within LC 2. In contrast, for methods G5 and R2, even the most intensive reuse scenario becomes negligible once a substantial biogenic carbon credit is assigned to LC 2, further confirming that methodological choices in biogenic carbon modelling and allocation continue to dominate the final climate change impact.

5. Service life – Sensitivity analysis

5.1 Introduction

In the baseline scenario, two life cycles of 50 years are assumed. Since emissions are assessed using dynamic LCA, changing the service life directly affects the timing of reuse processes, waste processes, and biogenic carbon release within the assessed time horizon. As a result, service life becomes an important parameter influencing the climate change impact of reused structural timber systems.

This chapter evaluates the influence of service life assumptions by comparing life cycles of 40, 50, and 60 years. The selected values are based on both practical observations and existing assessment frameworks, including the 60-year service life applied in TOTEM. All other baseline assumptions remain unchanged, including the reuse scenario, density values, rotation periods, and allocation methods.

The chapter first evaluates the influence of service life on fossil and biogenic carbon emissions separately. Afterwards, the effect of changing the service life on the distribution of impacts between life cycles is assessed for selected allocation methods.

5.2 Impact on fossil carbon emissions

Production and construction emissions (Modules A1–A5) are inventoried at the start of the assessment period and are therefore unaffected by changes in service life. The influence of service life on fossil carbon emissions is consequently limited to the timing of reuse and waste processes. Figure 46 shows the influence of service life variation on the fossil carbon emissions associated with reuse processes.

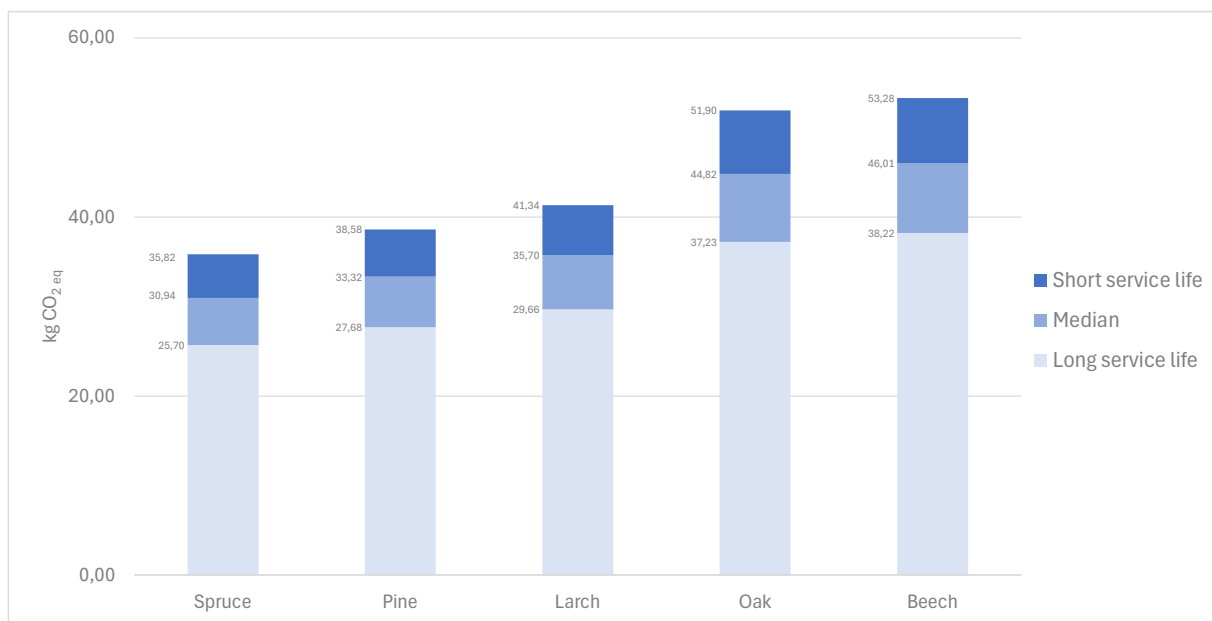


Figure 46. Fossil carbon emissions associated with reuse processes for different service life values

A shorter service life increases the climate change impact of reuse processes, as these emissions occur earlier in the assessment period and are therefore weighted more strongly in the dynamic

assessment. Conversely, longer service lives reduce the impact by shifting reuse processes further into the future.

Nevertheless, the overall influence on fossil carbon emissions remains limited, since reuse and waste processes only contribute a small share to the total climate change impact. Waste processes show the same temporal behaviour. Shorter service lives increase their relative contribution, while service lives exceeding the 100-year assessment period shift these emissions outside the assessed time horizon. However, their overall contribution remains negligible compared to the total climate change impact. The corresponding results are included in Appendix J.

5.3 Impact on biogenic carbon emissions

For the growth approach, biogenic carbon uptake is always inventoried at the start of the assessment period and is therefore unaffected by changes in service life. In contrast, the regrowth approach distributes carbon uptake over time, meaning that changes in service life can also influence the amount of sequestration occurring within the 100-year assessment period. For both approaches, service life directly affects the timing of biogenic carbon release.

Figure 47 shows the influence of service life variation on biogenic carbon uptake under the regrowth approach and on the timing of biogenic carbon release.

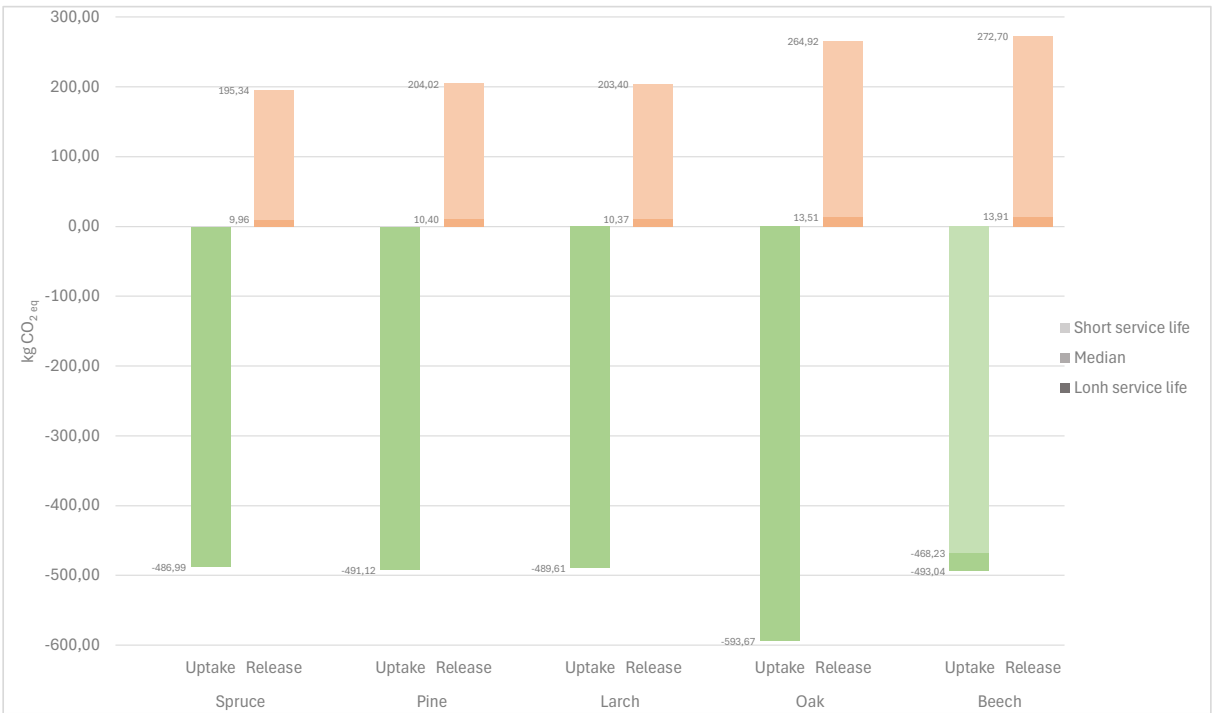


Figure 47. Biogenic carbon emissions for different service life values

For most species, service life variation has no influence on the total amount of biogenic carbon uptake. Since the rotation periods of spruce, pine, larch, and oak remain below 80 years, full sequestration is completed within the 100-year assessment period for both the short and median service life scenarios. Extending the service life beyond the baseline scenario equally has no effect, as uptake occurring after year 100 remains outside the assessment period regardless.

Beech forms an exception due to its median rotation period of 110 years. Since sequestration is not yet complete at year 80, a shorter service life of 40 years per life cycle results in a reduced sequestration credit compared to the baseline scenario, as a larger share of carbon uptake occurs beyond the system boundary and is therefore not credited within the assessment.

The influence of service life becomes substantially larger for biogenic carbon release. Shorter service lives shift carbon release to earlier points in time, significantly increasing its climate change impact in the dynamic assessment. Longer service lives delay release, reducing its contribution. For the maximum service life scenario, biogenic carbon release even occurs outside the 100-year assessment period entirely. The behaviour of methods G5 and R2 differs from this pattern and is discussed separately in Section 5.5. The influence of service life is therefore primarily governed by the timing of biogenic carbon release, rather than by changes in carbon uptake.

5.4 Comparison method G1 – R1

For methods G1 and R1, the second life cycle only contains reuse and waste processes, as discussed in Chapter 1. Figure 48 shows the influence of service life variation on LC 2.

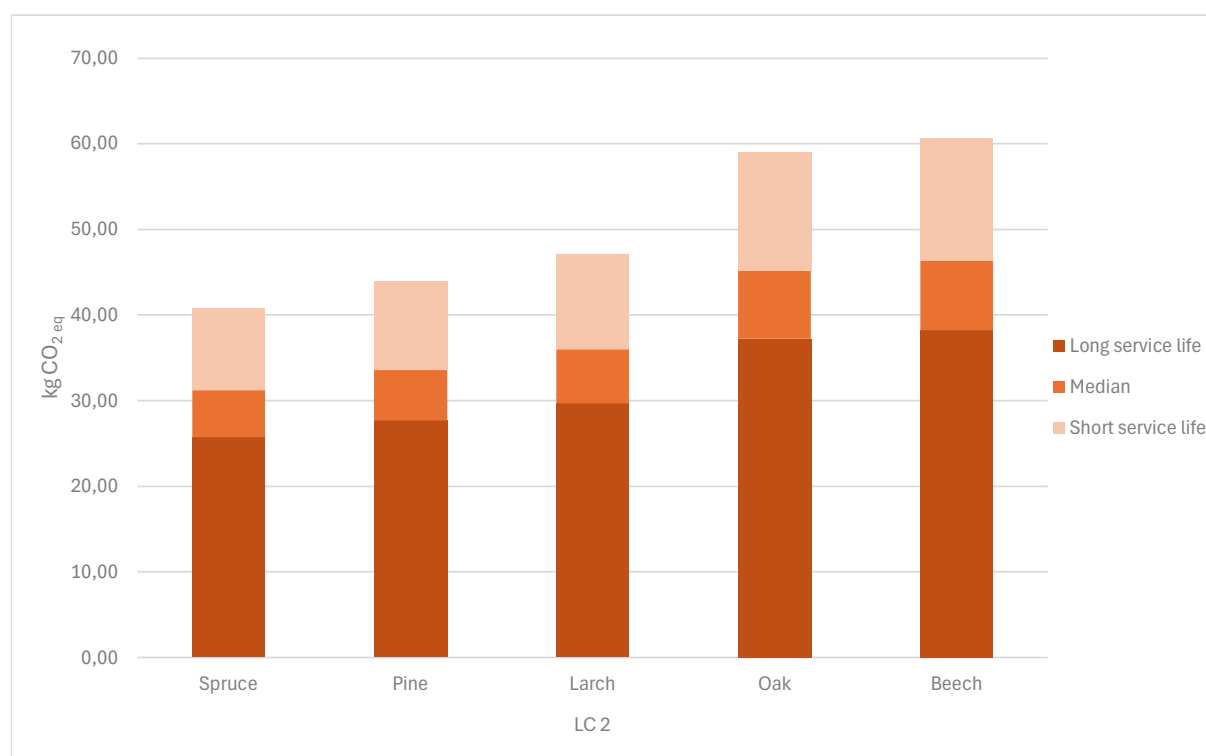


Figure 48. Impact of service life variation for allocation methods G1 and R1 on life cycle 2

A shorter service life increases the climate change impact of the second life cycle by shifting reuse and waste processes closer to the start of the assessment period. In contrast, longer service lives reduce these impacts due to their later timing. For service lives of 60 years per life cycle, waste processes occur outside the 100-year assessment period and are therefore no longer included in the results. Nevertheless, the overall variation remains limited.

Figure 49 illustrates the influence of service life variation on the first life cycle.

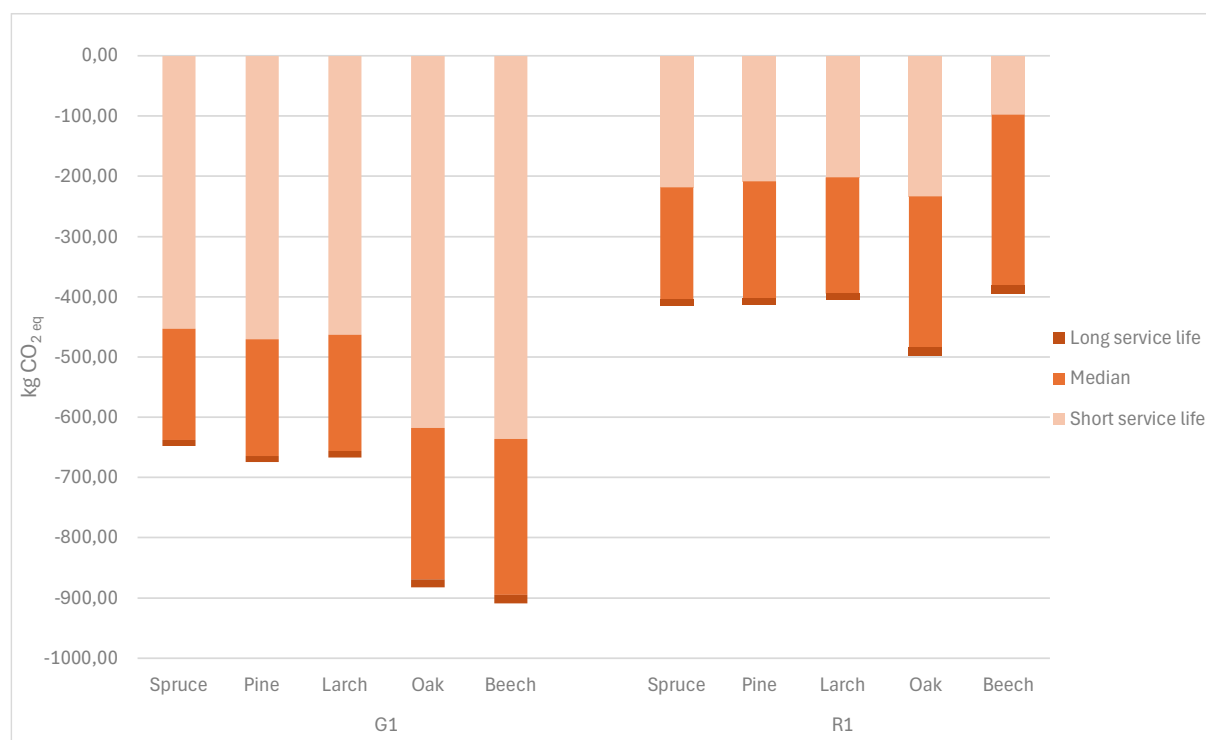


Figure 49. Impact of service life variation for allocation methods G1 and R1 on life cycle 1

For method G1, the influence of service life is almost entirely governed by the timing of biogenic carbon release. Since carbon uptake is fully credited at the start of the assessment period, changing the service life does not affect the sequestration credit. Shortening the service life shifts biogenic carbon release to an earlier point in time, substantially increasing its climate change impact. For the maximum service life scenario, release is pushed outside the 100-year assessment period, further reducing its contribution.

For method R1, the effect of release timing follows the same pattern as G1, but is more pronounced. Unlike G1, where the full sequestration credit is assigned at year 0, the regrowth approach distributes carbon uptake over time, meaning that earlier release is less effectively offset by the available sequestration credit. This effect is further amplified for species with longer rotation periods, as discussed in section 5.3.

5.5 Comparison method G5 – R2

For allocation methods G5 and R2, service life variation affects not only the timing of biogenic carbon flows, but also their distribution between life cycles. In contrast to methods G1 and R1, carbon uptake and release are transferred between life cycles, making the influence of service life more complex.

Figure 50 shows the influence of service life variation for allocation method G5.

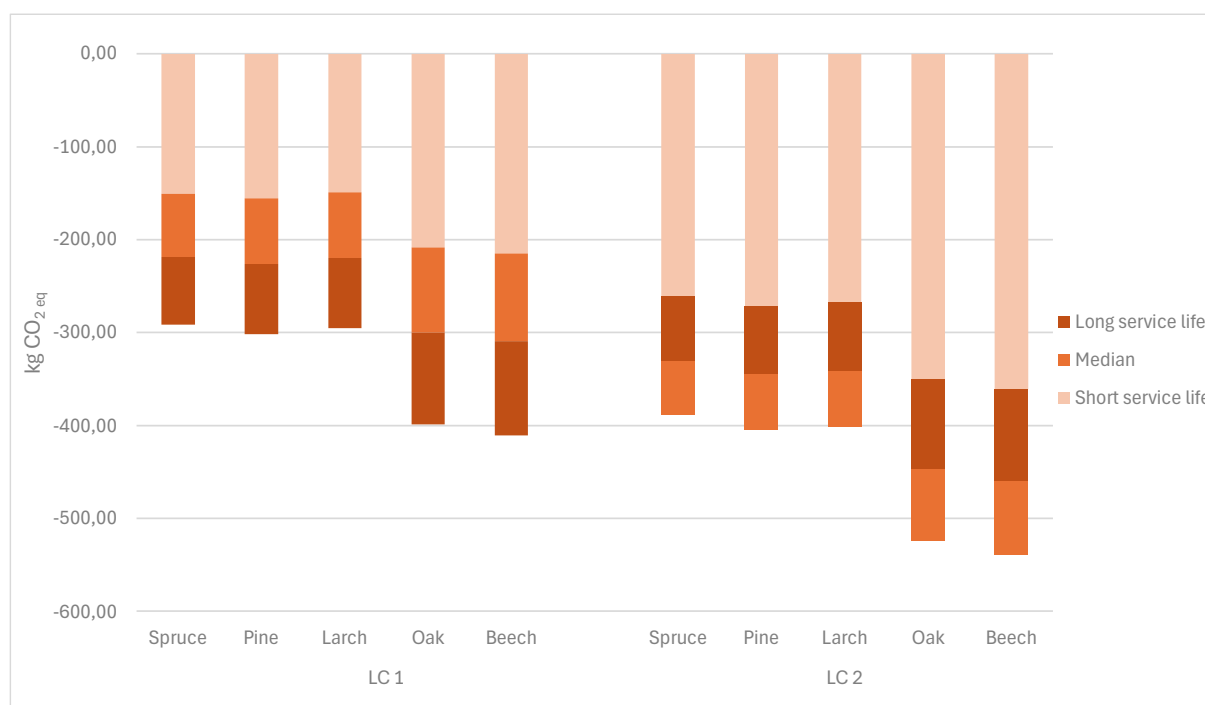


Figure 50. Impact of service life variation for allocation method G5

For the first life cycle, shorter service lives increase the climate change impact due to the earlier timing of biogenic carbon release. Longer service lives delay the release further into the future, reducing its contribution. Since release already occurs at year 50 in the baseline scenario (earlier than in G1 and R1 where release occurs at year 100) the influence of service life on LC 1 is more pronounced than for those methods.

For the second life cycle, the results are governed by the interaction between transferred uptake and delayed release. Shorter service lives shift both uptake and release to earlier points in time. Although this increases the sequestration credit allocated to LC 2, the earlier release dominates the results, leading to higher impacts. Longer service lives reduce the contribution of release but also delay the transfer of uptake. As a result, the baseline scenario generally results in the lowest climate change impact for LC 2.

Figure 51 shows the influence of service life variation for allocation method R2.

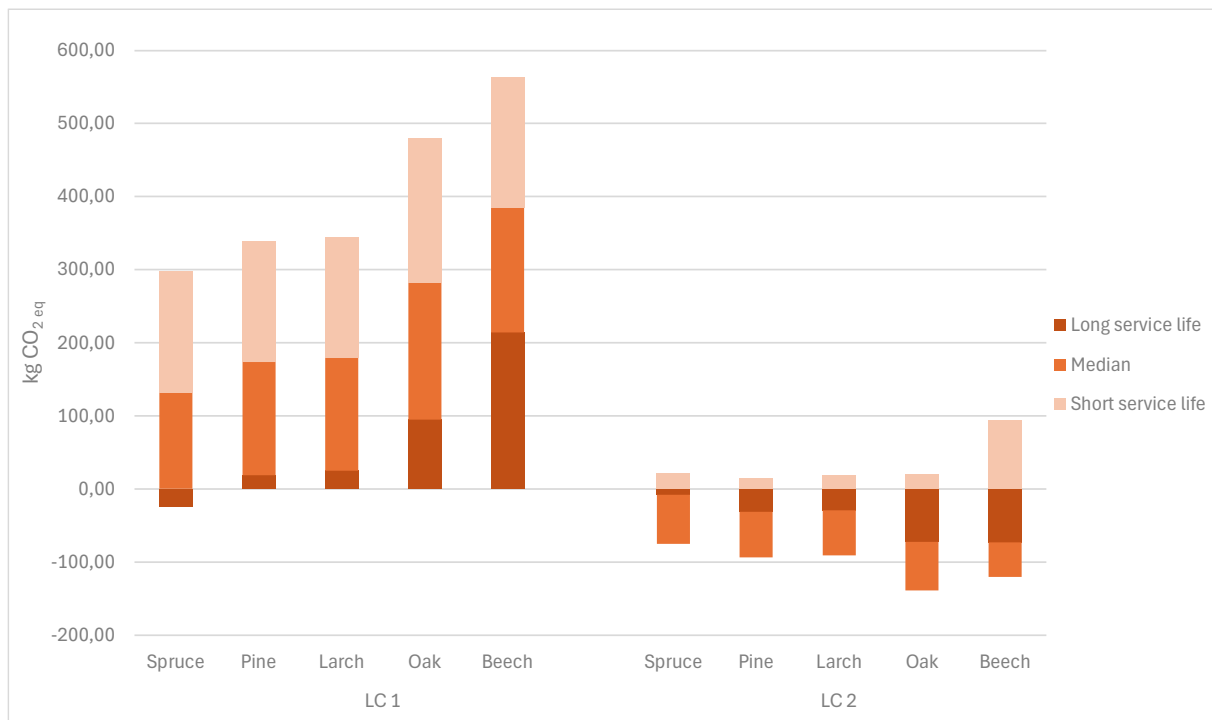


Figure 51. Impact of service life variation for allocation method R2

Method R2 demonstrates the strongest sensitivity to service life variation. For the first life cycle, shorter service lives reduce the amount of carbon uptake occurring within LC 1 while shifting biogenic carbon release to an earlier point in time. This results in substantially higher climate change impacts, especially for oak and beech, where longer rotation periods mean that a larger share of sequestration occurs after the end of the first life cycle. Longer service lives have the opposite effect: more uptake is assigned to LC 1, while release occurs later. For spruce, this can even result in a net negative impact for LC 1.

For the second life cycle, shorter service lives allocate more carbon uptake to LC 2, but this is not sufficient to offset the earlier biogenic carbon release occurring at year 80. As a result, the minimum service life scenario leads to the highest impacts for LC 2. Under the baseline scenario, release occurs at year 100 and is therefore strongly reduced in the dynamic assessment, while a substantial share of uptake is still assigned to LC 2. This results in the lowest impacts for most species. For the maximum service life scenario, release falls outside the 100-year assessment period, but less carbon uptake remains available for LC 2 because a larger share is allocated to LC 1. The impact therefore increases again compared to the baseline scenario, although it remains lower than for the minimum service life scenario.

The remaining allocation methods are included in Appendix J. For method G2, no biogenic carbon uptake is allocated to the second life cycle while the full release is assigned there, meaning it shows an even stronger sensitivity to service life variation than G1. The first life cycle remains largely unaffected, as the full sequestration credit is assigned regardless of service life. Methods G4 and R3 show similar trends to G1 and R1, as biogenic carbon uptake and release are shared between both life cycles. For method G3, the influence on LC 2 remains limited since the full uptake credit offsets the reuse and waste processes, while LC 1 shows a much stronger sensitivity as it carries production impacts and delayed biogenic carbon release without receiving any credit.

5.6 Conclusion

The results show that service life mainly influences the timing of emissions within the dynamic assessment. Shorter service lives consistently result in higher climate change impacts, as reuse, waste, and especially biogenic carbon release occur earlier in the assessed time horizon and are therefore weighted more strongly.

The influence on fossil carbon emissions remains limited, as production impacts are unaffected and reuse and waste processes contribute only a small share to the overall impact. For most species, service life has little influence on the total amount of biogenic carbon uptake, as sequestration is largely completed within the assessed period. In contrast, the timing of biogenic carbon release forms the dominant mechanism through which service life influences the climate change impact.

The strongest sensitivity is observed for methods G5 and R2, where service life affects both the timing of biogenic carbon release and the distribution of carbon uptake between life cycles, resulting in substantially larger impacts compared to methods G1 and R1.

Of all parameters assessed, service life shows the strongest influence on the dynamic climate change impact. These results further confirm that the choice of allocation method determines how strongly this influence manifests, reinforcing the central finding that methodological choices dominate the assessment of reused structural timber.

6. General conclusion

6.1 Interpretation and discussion

The results demonstrate that the choice of allocation method and biogenic carbon modelling approach is the dominant driver of the calculated climate change impact. Although production, reuse, and waste processes all contribute to the total impact, the decision of where to allocate biogenic carbon uptake and release, and whether to apply the growth or regrowth approach, determines the magnitude and direction of the results far more than any other factor.

The choice of allocation method also reflects a normative decision about the purpose of the assessment. Methods G1 and R1, and to an even greater extent G2, primarily promote the use of biobased materials. They allocate the largest climate benefits to the first life cycle, resulting in strongly negative impacts for LC 1 and positive impacts for LC 2. Method G3 instead favours reuse by transferring sequestration credits to the second life cycle. This results in the most negative impacts for LC 2, at the cost of a higher impact for LC 1. Methods G4 and R3 attempt to distribute benefits and burdens more fairly between both life cycles. G5 and R2 go further by treating each life cycle as independent, crediting each with its own uptake and holding each responsible for its own release. This results in net negative impacts for both life cycles in most scenarios.

The sensitivity analyses confirm this hierarchy. Reuse processes only become the dominant source of variation when no biogenic carbon is allocated to the second life cycle. Once even a partial credit is assigned, their contribution becomes almost negligible. Density drives both fossil emissions and biogenic carbon release proportionally, but this effect is offset when a sequestration credit is allocated. Rotation period only matters within the regrowth approach, where longer rotation periods can reduce the sequestration credit so strongly that the carbon storage advantage of denser hardwood species is entirely neutralised. Service life affects the results primarily through the timing of biogenic carbon release. In essence, the later the release and the earlier the uptake, the greater the climate benefit — making the influence of service life highly dependent on the chosen allocation method.

The choice of allocation method therefore precedes and governs all other methodological decisions. It determines which parameters matter, how much they matter, and in which direction they influence the final result.

From this perspective, the thesis also contributes to a broader understanding of how biogenic carbon can function as a genuine climate benefit within LCA. The results show that this benefit is not automatic. It depends on methodological choices regarding timing, allocation, and the number of life cycles considered. For reused timber in particular, where carbon storage is extended across multiple life cycles, these choices become especially consequential. A well-considered allocation framework can make the climate benefit of reused biobased materials explicit and robust, while poorly defined assumptions risk overstating, overlooking, or even reversing this benefit entirely.

6.2 Limitations and future perspectives

This thesis is subject to some limitations. Firstly, limited empirical data is currently available regarding the practical reuse of structural timber, including actual service lives, reuse rates, transport distances, and required processing steps. As a result, several assumptions were required to model the reuse scenarios and life cycle configurations.

In addition, performing dynamic LCAs of reused timber requires information that is often difficult to obtain in practice. For the second life cycle, limited knowledge is typically available regarding the material's history and prior use. For the first life cycle, allocating sequestration credits or anticipating future reuse assumes outcomes that cannot be guaranteed at the time of assessment. This introduces uncertainties that are difficult to quantify but potentially significant for the reliability of the results.

Finally, this thesis only assessed the climate change impact indicator and did not include other environmental impact categories. Consequently, the conclusions are limited to climate-related impacts and do not represent the total environmental performance of reused structural timber systems.

Nevertheless, by explicitly quantifying these differences, this thesis provides a concrete basis for further discussion on how biogenic carbon could be modelled and allocated in the assessment of reused construction materials, particularly as circular construction strategies become more prominent in policy and practice.

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Appendix A: Societal reflection

Although this research is primarily technical in nature, it relates to broader societal challenges regarding climate change, resource use, and the transition towards a more circular construction sector. As the environmental impact of construction materials becomes increasingly important within policy and practice, the way these impacts are assessed may influence future material choices and construction strategies.

From an environmental perspective, this thesis highlights the potential advantages of both biobased materials and material reuse. Biobased materials often result in lower climate change impacts than conventional materials such as steel and concrete. Timber can also temporarily store atmospheric carbon during tree growth and throughout its service life. However, the effects related to biogenic carbon storage are often not explicitly included within conventional life cycle assessment approaches. By dynamically assessing carbon uptake, storage, and release over time, this research provides additional insights into how biogenic carbon may influence the calculated climate change impact of timber construction. A more explicit consideration of biogenic carbon within environmental assessments may help increase the recognition of timber as a low-impact construction material.

The reuse of structural timber can further extend the storage period of biogenic carbon while reducing the demand for newly produced materials. By investigating reused timber across multiple life cycles, this research contributes to a better understanding of the environmental value of reuse. In this way, the thesis supports the transition towards more circular construction practices.

This research is also relevant for professionals involved in environmental assessment and material selection within the construction sector. The results demonstrate that assumptions regarding carbon storage, allocation, and life cycles can strongly influence the climate change impact of reused timber systems. A better understanding of these mechanisms may support designers, engineers, and policymakers in making more informed decisions regarding circular and biobased construction materials. The thesis also highlights the importance of developing clearer guidance for assessing reused construction materials within future LCA standards.

From an economic perspective, this research relates to the broader transition from a linear to a more circular construction sector. Conventional construction practices often rely on the continuous extraction of new raw materials and the disposal of materials at the end of their service life. The reuse of structural timber instead aims to retain material value over multiple life cycles and reduce the dependence on virgin material production.

More broadly, this thesis contributes to the ongoing discussion surrounding sustainable construction and the role of the built environment in addressing climate change. The research underlines that the environmental performance of construction materials is not only determined by the materials themselves, but also by the way their impacts are assessed and interpreted.

Appendix B: Reflection on use of artificial intelligence

Throughout this thesis, artificial intelligence (AI) tools were used as supportive tools during the writing and editing process. AI mainly helped with the structure, clarity, grammar, and academic tone of the text. In addition, it was used to discuss interpretations of results, refine formulations, and provide feedback on the coherence and readability of different thesis sections. AI was also used for formatting and layout-related tasks.

Overall, AI did not replace critical thinking or original research, but assisted in improving the clarity, consistency, and readability of the final result while functioning solely as a supportive tool.

Appendix C: Values and assumptions

Table 1. Overview of densities

Source:		Joint Research Centre (Blujdea et al., 2024)							Petráš et al., 2019, 2020	Median	
Wood species		Belgium	The Netherlands	Germany	France	Denmark	Austria	Luxembourg	-	-	
Picea Abies	Spruce	380	380	470	380	380	400	400	484,80	390	kg/m ³
Pinus sylvestris	Pine	420	420	320	430	380	420	-	477,60	420	kg/m ³
Larix decidua	Larch	440	450	370	-	-	460	-	566,82	450	kg/m ³
Quercus Robur	Oak	540	570	540	560	560	580	580	728,50	565	kg/m ³
Fagus Sylvatica	Beech	590	620	530	560	560	580	580	694,64	580	kg/m ³

Table 2. Overview of rotation periods

Source:		Joint Research Centre (Blujdea et al., 2024)							Median	
Wood species		Belgium	The Netherlands	Germany	France	Denmark	Austria	Luxembourg	-	
Picea Abies	Spruce	50	60	80	70	-	110	60	65	Years
Pinus sylvestris	Pine	40	50	80	70	-	80	-	70	Years
Larix decidua	Larch	55	60	80	-	-	120	-	70	Years
Quercus Robur	Oak	-	65	80	110	-	80	200	80	Years
Fagus Sylvatica	Beech	-	65	80	110	-	110	160	110	Years

Table 3. Overview of carbon fractions

Source:		Doraisami et al., 2022	
Wood species		-	
Picea Abies	Spruce	50,42	%
Pinus sylvestris	Pine	48,90	%
Larix decidua	Larch	45,50	%
Quercus Robur	Oak	47,20	%
Fagus Sylvatica	Beech	47,33	%

Table 4. Overview of Dynamic characterization factors (DCF)

Year	DCF	Year	DCF
1	1,000	51	0,586
2	0,993	52	0,576
3	0,986	53	0,566
4	0,979	54	0,556
5	0,972	55	0,546
6	0,965	56	0,536
7	0,958	57	0,526
8	0,950	58	0,515
9	0,943	59	0,505
10	0,936	60	0,495
11	0,928	61	0,484
12	0,921	62	0,474
13	0,913	63	0,463
14	0,906	64	0,452
15	0,898	65	0,442
16	0,890	66	0,431
17	0,883	67	0,420
18	0,875	68	0,409
19	0,867	69	0,398
20	0,859	70	0,387
21	0,851	71	0,375
22	0,843	72	0,364
23	0,835	73	0,353
24	0,827	74	0,341
25	0,819	75	0,330
26	0,811	76	0,318
27	0,803	77	0,307
28	0,794	78	0,295
29	0,786	79	0,283
30	0,777	80	0,271
31	0,769	81	0,259
32	0,760	82	0,247
33	0,752	83	0,235
34	0,743	84	0,222
35	0,734	85	0,210
36	0,725	86	0,197
37	0,717	87	0,185
38	0,708	88	0,172
39	0,699	89	0,160
40	0,690	90	0,147
41	0,680	91	0,134
42	0,671	92	0,121
43	0,662	93	0,108
44	0,653	94	0,095
45	0,643	95	0,081
46	0,634	96	0,068
47	0,624	97	0,055
48	0,615	98	0,041
49	0,605	99	0,028
50	0,596	100	0,014

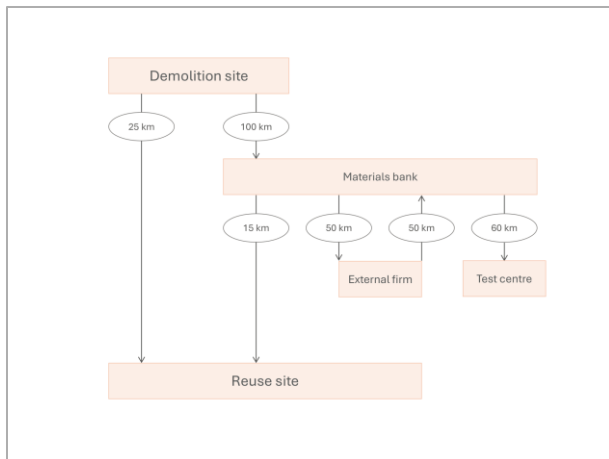


Figure 1. Assumptions regarding transport distances for reuse scenarios (Feys & Defever, 2025)

Appendix D: SimaPro processes and input data

Table 1. SimaPro processes and input data for 1 m³ of new structural timber

Production and transport of 1m ³ structural timber							
Description	SimaPro process	Spruce	Pine	Larch	Oak	Beech	
A1- A3		Quantity					Unit
Production	Sawnwood, beam, softwood, dried (u=10%), planed (Europe without Switzerland) Cut-off, S	423,93	456,54	489,15	-	-	kg
	Sawnwood, beam, hardwood, dried (u=10%), planed (Europe without Switzerland) Cut-off, S	-	-	-	614,16	630,46	kg
A4		Quantity					Unit
Transport from factory to site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	42,393	45,654	48,915	61,416	63,046	tkm

Table 2. SimaPro processes and input data for end-of-life modelling of 1 m³ of structural timber

End of life 1m ³ structural timber							
Description	SimaPro process	Spruce	Pine	Larch	Oak	Beech	
C1		Quantity					Unit
Inputs from technosphere: electricity/heat	Diesel, burned in building machine (GLO) market for diesel, burned in building machine Cut-off, S	0,0437	0,0437	0,0437	0,0437	0,0437	MJ/kg
Emissions to air	Particulates, < 2.5 um	0,000017	0,000017	0,000017	0,000017	0,000017	kg/kg
	Particulates, > 2.5 um, and < 10um	0,000063	0,000063	0,000063	0,000063	0,000063	kg/kg
	Particulates, > 10 um	0,000084	0,000084	0,000084	0,000084	0,000084	kg/kg
C2		Quantity					Unit
Transport to incineration facility	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	55,11	59,35	63,59	79,84	81,96	tkm
C4		Quantity					Unit
Incineration	Waste wood, untreated (CH) municipal incineration Cut-off, S	423,93	456,54	489,15	614,16	630,46	kg

Table 3. SimaPro processes and input data for auxiliary materials used in 1 m³ of new structural timber

Production and transport of auxiliary materials							
Description	SimaPro process	Spruce	Pine	Larch	Oak	Beech	
A1- A3		Quantity					Unit
Production of packaging film	Packaging film, low density polyethylene (RER) packaging film production, low density polyethylene Cut-off, S	0,542	0,583	0,625	0,785	0,806	kg
Production of plastic straps	Polypropylene, granulate (RER) polypropylene production, granulate Cut-off, S	0,067	0,072	0,078	0,097	0,100	kg
A4		Quantity					Unit
Transport of packaging film to the site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,0325	0,0350	0,0375	0,0471	0,0483	tkm
Transport of packaging film to the site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,0313	0,0337	0,0362	0,0454	0,0466	tkm
Transport of packaging film to the site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,0017	0,0018	0,0020	0,0025	0,0025	tkm
Transport of plastic straps to site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,0040	0,0043	0,0047	0,0058	0,0060	tkm
Transport of plastic straps to site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,0039	0,0042	0,0045	0,0056	0,0058	tkm
Transport of plastic straps to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,0002	0,0002	0,0002	0,0003	0,0003	tkm
C2		Quantity					Unit
Transport of packaging film to waste treatment	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,065	0,070	0,075	0,094	0,097	tkm
Transport of plastic straps to waste treatment	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,008	0,009	0,009	0,012	0,012	tkm
C4		Quantity					Unit
Electricity input in waste sorting from packaging film	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,001191748579	0,001283421547	0,001375094514	0,001726521613	0,001772344041	kWh
Input hydraulic excavator in waste sorting of packaging film	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,000640311938	0,000689566702	0,000738821467	0,000927638949	0,000952258780	m ³
Input sorting facility in waste sorting of packaging film	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,0000000000054	0,0000000000058	0,0000000000063	0,0000000000078	0,0000000000081	p
Electricity input in waste sorting of plastic straps	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,000147941203	0,000159321295	0,000170701388	0,000214326821	0,000220015122	kWh
Input hydraulic excavator in waste sorting of plastic straps	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,000079486999	0,000085601384	0,000091715768	0,000115155180	0,000118211435	m ³
Input sorting facility in waste sorting of plastic straps	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,0000000000007	0,0000000000007	0,0000000000008	0,0000000000010	0,0000000000010	p
Landfill of packaging film	Waste polyethylene (CH) treatment of waste polyethylene, sanitary landfill Cut-off, S	0,0542	0,0583	0,0625	0,0785	0,0806	kg
Incineration of packaging film	Waste polyethylene (CH) treatment of waste polyethylene, municipal incineration FAE Cut-off, S	0,0572	0,0616	0,0660	0,0828	0,0850	kg
Landfill of plastic straps	Waste polypropylene (CH) treatment of waste polypropylene, sanitary landfill Cut-off, S	0,0542	0,0583	0,0625	0,0785	0,0806	kg
Incineration of plastic straps	Waste polypropylene (CH) treatment of waste polypropylene, municipal incineration FAE Cut-off, S	0,0572	0,0616	0,0660	0,0828	0,0850	kg

Note: The listed auxiliary materials are modelled within module A5 because they are related to installation and packaging activities occurring during the construction phase.

Table 4. SimaPro processes and input data for reuse scenario 1

Reuse scenario 1							
Description	SimaPro process	Spruce	Pine	Larch	Oak	Beech	
Transport		Quantity					Unit
Transport to new construction site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	10,598	11,414	12,229	15,354	15,762	tkm
Energy consumption and other consumption		Quantity					Unit
Ascending and descending with electric scissor lift (3x)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Relocation with electric scissor lift (3x)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Lifting and lowering beams with a crawler excavator	Diesel, burned in building machine (GLO) market for diesel, burned in building machine Cut-off, S						
Fastening or loosening struts with an electric drill and screwdriver	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Tighten or loosen bolts (2x) with electric drill and screwdriver	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Lifting beams on transport with a crawler excavator	Diesel, burned in building machine (GLO) market for diesel, burned in building machine Cut-off, S						
Unloading beams from transport using an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Reorganising a beam in the stockroom with an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Cutting widthwise with a hand-held circular saw	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,019	0,020	0,022	0,027	0,028	kWh
Auxiliary materials		Quantity					Unit
Production of waterproof cover	Packaging film, low density polyethylene (RER) packaging film production, low density polyethylene Cut-off, S	1,599	1,722	1,845	2,316	2,378	kg
Transport of waterproof cover to site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,092	0,100	0,107	0,134	0,138	tkm
Transport of waterproof cover to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,005	0,005	0,006	0,007	0,007	tkm
Transport of waterproof cover to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,192	0,207	0,221	0,278	0,285	tkm
Electricity input in waste sorting from waterproof cover	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,004	0,004	0,004	0,005	0,005	kWh
Input hydraulic excavator in waste sorting of waterproof cover	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m ³
Input sorting facility in waste sorting of waterproof cover	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000016	0,00000000017	0,00000000018	0,00000000023	0,00000000024	p
Landfill of waterproof cover	Waste polyethylene (CH) treatment of waste polyethylene, sanitary landfill Cut-off, S	0,160	0,172	0,184	0,232	0,238	kg
Incineration of waterproof cover	Waste polyethylene (CH) treatment of waste polyethylene, municipal incineration FAE Cut-off, S	1,359	1,464	1,568	1,969	2,021	kg

Note: The reuse scenarios and associated reclamation processes are based on the case studies reported by Feys & Defever (2025). The presented values were recalculated and proportionally scaled by weight according to the species-specific densities applied in this study. Processes indicated in light grey were excluded from the calculations due to their project-specific nature.

Table 5. SimaPro processes and input data for reuse scenario 2

Reuse scenario 2							
Description	SimaPro process	Spruce	Pine	Larch	Oak	Beech	
Transport		Quantity					Unit
Transport to materials bank	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	42,393	45,654	48,915	61,416	63,046	tkm
Transport to new construction site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	6,359	6,848	7,337	9,212	9,457	tkm
Energy consumption and other consumption		Quantity					Unit
Ascending and descending with electric scissor lift (3x)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Relocation with electric scissor lift (3x)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Lifting and lowering beams with a crawler excavator	Diesel, burned in building machine (GLO) market for diesel, burned in building machine Cut-off, S						
Fastening or loosening struts with an electric drill and screwdriver	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Tighten or loosen bolts (2x) with electric drill and screwdriver	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Lifting beams on transport with a crawler excavator	Diesel, burned in building machine (GLO) market for diesel, burned in building machine Cut-off, S						
Unloading beams from transport using an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Reorganising a beam in the stockroom with an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Unloading a beam from stock using an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Removing metal elements with a metal detector	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,00025	0,00027	0,00029	0,00037	0,00038	kWh
Cutting widthwise with a hand-held circular saw	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,019	0,020	0,022	0,027	0,028	kWh
Making openings (±12x) with a hammer drill with stand	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,031	0,034	0,036	0,046	0,047	kWh
Cleaning surfaces with an electric wire brush	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	1,506	1,621	1,737	2,181	2,239	kWh
Cleaning surfaces with a high-pressure cleaner (electricity fraction)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	2,677	2,882	3,088	3,878	3,981	kWh
Cleaning surfaces with a high-pressure cleaner (fraction water)	Tap water (Europe without Switzerland) market for tap water Cut-off, S	635,680	684,578	733,477	920,928	945,370	kg
Cleaning surfaces with a parquet sanding machine	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	2,509	2,702	2,895	3,635	3,732	kWh
Lifting beams during transport with an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Abrasive blasting	Abrasive blasting, alumina, carbon steel substrate (GLO) abrasive blasting, alumina, carbon steel substrate Cut-off, S	0,241	0,259	0,278	0,349	0,358	m ²
Auxiliary materials		Quantity					Unit
Production of waterproof cover	Packaging film, low density polyethylene (RER) packaging film production, low density polyethylene Cut-off, S	1,599	1,722	1,845	2,316	2,378	kg
Production of (fire-resistant) paint	Alkyd paint, white, without water, in 60% solution state (RER) alkyd paint production, white, water-based, product in 60% solution state Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production of varnish	Acrylic varnish, with water, in 53% solution state (RER) acrylic varnish production, with water, in 53% solution state Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production and transport of linseed oil	Vegetable oil, refined (GLO) market for vegetable oil, refined Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production of epoxy resin for filling holes and cracks	Epoxy resin, liquid (RER) epoxy resin production, liquid Cut-off, S	0,385	0,415	0,444	0,558	0,573	kg
Transport of waterproof cover to site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,092	0,100	0,107	0,134	0,138	tkm
Transport of waterproof cover to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,005	0,005	0,006	0,007	0,007	tkm
Transport of paint/varnish to site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,160	0,172	0,184	0,232	0,238	tkm
Transport of paint/varnish to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,063	0,067	0,072	0,091	0,093	tkm
Transport of paint/varnish to site	Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 Cut-off, S	0,011	0,012	0,013	0,016	0,017	tkm
Transport of epoxy resin to site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,035	0,037	0,040	0,050	0,052	tkm
Transport of epoxy resin to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,014	0,015	0,016	0,020	0,020	tkm
Transport of epoxy resin to site	Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 Cut-off, S	0,002	0,003	0,003	0,004	0,004	tkm
Transport of waterproof cover to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,192	0,207	0,221	0,278	0,285	tkm
Transport of paint/varnish/linseed oil to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,231	0,249	0,266	0,335	0,343	tkm
Transport of epoxy resin to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,050	0,054	0,058	0,073	0,074	tkm

Electricity input in waste sorting from waterproof cover	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,004	0,004	0,004	0,005	0,005	kWh
Input hydraulic excavator in waste sorting of waterproof cover	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input sorting facility in waste sorting of waterproof cover	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000016	0,00000000017	0,00000000018	0,00000000023	0,00000000024	p
Electricity input in waste sorting of paint/varnish/linseed oil	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,004	0,004	0,005	0,006	0,006	kWh
Input hydraulic excavator in paint waste sorting	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input sorting facility in waste sorting of paint/varnish/linseed oil	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000018	0,00000000019	0,00000000020	0,00000000026	0,00000000026	p
Input hydraulic excavator in waste sorting of varnish	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input hydraulic excavator in waste sorting of linseed oil	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input electricity in waste sorting of epoxy resin	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,001	0,001	0,001	0,001	0,001	kWh
Input hydraulic excavator in waste sorting of epoxy resin	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,0003	0,0004	0,0004	0,0005	0,0005	m³
Input sorting facility in waste sorting of epoxy resin	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000004	0,00000000004	0,00000000004	0,00000000006	0,00000000006	p
Landfill of waterproof cover	Waste polyethylene (CH) treatment of waste polyethylene, sanitary landfill Cut-off, S	0,160	0,172	0,184	0,232	0,238	kg
Incineration of waterproof cover	Waste polyethylene (CH) treatment of waste polyethylene, municipal incineration FAE Cut-off, S	1,359	1,464	1,568	1,969	2,021	kg
Incineration paint/varnish/linseed oil	Waste paint (CH) treatment of waste paint, municipal incineration FAE Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Incineration of epoxy resin	Hazardous waste, for incineration (Europe without Switzerland) treatment of hazardous waste, hazardous waste incineration Cut-off, S	0,385	0,415	0,444	0,558	0,573	kg

Note: The reuse scenarios and associated reclamation processes are based on the case studies reported by Feys & Defever (2025). The presented values were recalculated and proportionally scaled by weight according to the species-specific densities applied in this study. Processes indicated in light grey were excluded from the calculations due to their project-specific nature.

Table 6. SimaPro processes and input data for reuse scenario 3

Reuse scenario 3							
Description	SimaPro process	Spruce	Pine	Larch	Oak	Beech	
Transport		Quantity					Unit
Transport to materials bank	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	42,393	45,654	48,915	61,416	63,046	tkm
Transport to external firm	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	21,197	22,827	24,458	30,708	31,523	tkm
Transport to test centre	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	25,436	27,392	29,349	36,850	37,828	tkm
Transport to new construction site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	6,359	6,848	7,337	9,212	9,457	tkm
Energy consumption and other consumption		Quantity					Unit
Ascending and descending with electric scissor lift (3x)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Relocation with electric scissor lift (3x)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Lifting and lowering beams with a crawler excavator	Diesel, burned in building machine (GLO) market for diesel, burned in building machine Cut-off, S						
Fastening or loosening struts with an electric drill and screwdriver	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Tighten or loosen bolts (2x) with electric drill and screwdriver	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Lifting beams on transport with a crawler excavator	Diesel, burned in building machine (GLO) market for diesel, burned in building machine Cut-off, S						
Unloading beams from transport using an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Reorganising a beam in the stockroom with an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Unloading a beam from stock using an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						

Removing metal elements with a metal detector	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,00025	0,00027	0,00029	0,00037	0,00038	kWh
Cutting widthwise with a hand-held circular saw	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,019	0,020	0,022	0,027	0,028	kWh
Making openings (±12x) with a hammer drill with stand	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,031	0,034	0,036	0,046	0,047	kWh
Cutting at height with a band saw with feed mechanism	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,888	0,957	1,025	1,287	1,321	kWh
Planing with a wide planer	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,101	0,109	0,116	0,146	0,150	kWh
Cleaning surfaces with an electric wire brush	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	1,506	1,621	1,737	2,181	2,239	kWh
Cleaning surfaces with a high-pressure cleaner (electricity fraction)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	2,677	2,882	3,088	3,878	3,981	kWh
Cleaning surfaces with a high-pressure cleaner (fraction water)	Tap water (Europe without Switzerland) market for tap water Cut-off, S	635,680	684,578	733,477	920,928	945,370	kg
Cleaning surfaces with a parquet sanding machine	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	2,509	2,702	2,895	3,635	3,732	kWh
Lifting beams during transport with an electric forklift	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Abrasive blasting	Abrasive blasting, alumina, carbon steel substrate (GLO) abrasive blasting, alumina, carbon steel substrate Cut-off, S	0,241	0,259	0,278	0,349	0,358	m²
Auxiliary materials		Quantity					Unit
Production of waterproof cover	Packaging film, low density polyethylene (RER) packaging film production, low density polyethylene Cut-off, S	1,599	1,722	1,845	2,316	2,378	kg
Production of (fire-resistant) paint	Alkyd paint, white, without water, in 60% solution state (RER) alkyd paint production, white, water-based, product in 60% solution state Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production of varnish	Acrylic varnish, with water, in 53% solution state (RER) acrylic varnish production, with water, in 53% solution state Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production and transport of linseed oil	Vegetable oil, refined (GLO) market for vegetable oil, refined Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production of epoxy resin for filling holes and cracks	Epoxy resin, liquid (RER) epoxy resin production, liquid Cut-off, S	0,385	0,415	0,444	0,558	0,573	kg
Transport of waterproof cover to site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,092	0,100	0,107	0,134	0,138	tkm
Transport of waterproof cover to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,005	0,005	0,006	0,007	0,007	tkm
Transport of paint/varnish to site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,160	0,172	0,184	0,232	0,238	tkm
Transport of paint/varnish to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,063	0,067	0,072	0,091	0,093	tkm
Transport of paint/varnish to site	Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 Cut-off, S	0,011	0,012	0,013	0,016	0,017	tkm
Transport of epoxy resin to site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,035	0,037	0,040	0,050	0,052	tkm
Transport of epoxy resin to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,014	0,015	0,016	0,020	0,020	tkm
Transport of epoxy resin to site	Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 Cut-off, S	0,002	0,003	0,003	0,004	0,004	tkm
Transport of waterproof cover to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,192	0,207	0,221	0,278	0,285	tkm
Transport of paint/varnish/linseed oil to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,231	0,249	0,266	0,335	0,343	tkm
Transport of epoxy resin to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,050	0,054	0,058	0,073	0,074	tkm

Electricity input in waste sorting from waterproof cover	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,004	0,004	0,004	0,005	0,005	kWh
Input hydraulic excavator in waste sorting of waterproof cover	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m ³
Input sorting facility in waste sorting of waterproof cover	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000016	0,00000000017	0,00000000018	0,00000000023	0,00000000024	p
Electricity input in waste sorting of paint/varnish/linseed oil	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,004	0,004	0,005	0,006	0,006	kWh
Input hydraulic excavator in paint waste sorting	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m ³
Input sorting facility in waste sorting of paint/varnish/linseed oil	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000018	0,00000000019	0,00000000020	0,00000000026	0,00000000026	p
Input hydraulic excavator in waste sorting of varnish	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m ³
Input hydraulic excavator in waste sorting of linseed oil	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m ³
Input electricity in waste sorting of epoxy resin	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,001	0,001	0,001	0,001	0,001	kWh
Input hydraulic excavator in waste sorting of epoxy resin	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,0003	0,0004	0,0004	0,0005	0,0005	m ³
Input sorting facility in waste sorting of epoxy resin	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000004	0,00000000004	0,00000000004	0,00000000006	0,00000000006	p
Landfill of waterproof cover	Waste polyethylene (CH) treatment of waste polyethylene, sanitary landfill Cut-off, S	0,160	0,172	0,184	0,232	0,238	kg
Incineration of waterproof cover	Waste polyethylene (CH) treatment of waste polyethylene, municipal incineration FAE Cut-off, S	1,359	1,464	1,568	1,969	2,021	kg
Incineration paint/varnish/linseed oil	Waste paint (CH) treatment of waste paint, municipal incineration FAE Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Incineration of epoxy resin	Hazardous waste, for incineration (Europe without Switzerland) treatment of hazardous waste, hazardous waste incineration Cut-off, S	0,385	0,415	0,444	0,558	0,573	kg

Note: The reuse scenarios and associated reclamation processes are based on the case studies reported by Feys & Defever (2025). The presented values were recalculated and proportionally scaled by weight according to the species-specific densities applied in this study. Processes indicated in light grey were excluded from the calculations due to their project-specific nature.

Table 7. SimaPro processes and input data for reuse scenario 4

Reuse scenario 4							
Description	SimaPro process	Spruce	Pine	Larch	Oak	Beech	
Energy consumption and other consumption		Quantity					Unit
Making openings (±12x) with a hammer drill with stand	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,031	0,034	0,036	0,046	0,047	kWh
Cleaning surfaces with an electric wire brush	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	1,506	1,621	1,737	2,181	2,239	kWh
Cleaning surfaces with a high-pressure cleaner (electricity fraction)	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	2,677	2,882	3,088	3,878	3,981	kWh
Cleaning surfaces with a high-pressure cleaner (fraction water)	Tap water (Europe without Switzerland) market for tap water Cut-off, S	635,680	684,578	733,477	920,928	945,370	kg
Cleaning surfaces with a parquet sanding machine	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	2,509	2,702	2,895	3,635	3,732	kWh
Abrasive blasting	Abrasive blasting, alumina, carbon steel substrate (GLO) abrasive blasting, alumina, carbon steel substrate Cut-off, S	0,241	0,259	0,278	0,349	0,358	m ²
Ascending and descending with electric scissor lift for performing operations	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						
Moving with an electric scissor lift to perform operations	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S						

Auxiliary materials		Quantity					Unit
Production of waterproof cover	Packaging film, low density polyethylene (RER) packaging film production, low density polyethylene Cut-off, S	1,599	1,722	1,845	2,316	2,378	kg
Production of (fire-resistant) paint	Alkyd paint, white, without water, in 60% solution state (RER) alkyd paint production, white, water-based, product in 60% solution state Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production of varnish	Acrylic varnish, with water, in 53% solution state (RER) acrylic varnish production, with water, in 53% solution state Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production and transport of linseed oil	Vegetable oil, refined (GLO) market for vegetable oil, refined Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Production of epoxy resin for filling holes and cracks	Epoxy resin, liquid (RER) epoxy resin production, liquid Cut-off, S	0,385	0,415	0,444	0,558	0,573	kg
Transport of waterproof cover to site	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,092	0,100	0,107	0,134	0,138	tkm
Transport of waterproof cover to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,005	0,005	0,006	0,007	0,007	tkm
Transport of paint/varnish to site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,160	0,172	0,184	0,232	0,238	tkm
Transport of paint/varnish to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,063	0,067	0,072	0,091	0,093	tkm
Transport of paint/varnish to site	Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 Cut-off, S	0,011	0,012	0,013	0,016	0,017	tkm
Transport of epoxy resin to site	Transport, freight, lorry, >32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, >32 metric ton, diesel, EURO 5 Cut-off, S	0,035	0,037	0,040	0,050	0,052	tkm
Transport of epoxy resin to site	Transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 7.5-16 metric ton, diesel, EURO 5 Cut-off, S	0,014	0,015	0,016	0,020	0,020	tkm
Transport of epoxy resin to site	Transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 3.5-7.5 metric ton, diesel, EURO 5 Cut-off, S	0,002	0,003	0,003	0,004	0,004	tkm
Transport of waterproof cover to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,192	0,207	0,221	0,278	0,285	tkm
Transport of paint/varnish/linseed oil to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,231	0,249	0,266	0,335	0,343	tkm
Transport of epoxy resin to waste processing	Transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 (RER) transport, freight, lorry, 16-32 metric ton, diesel, EURO 5 Cut-off, S	0,050	0,054	0,058	0,073	0,074	tkm
Electricity input in waste sorting from waterproof cover	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,004	0,004	0,004	0,005	0,005	kWh
Input hydraulic excavator in waste sorting of waterproof cover	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input sorting facility in waste sorting of waterproof cover	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000016	0,00000000017	0,00000000018	0,00000000023	0,00000000024	p
Electricity input in waste sorting of paint/varnish/linseed oil	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,004	0,004	0,005	0,006	0,006	kWh
Input hydraulic excavator in paint waste sorting	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input sorting facility in waste sorting of paint/varnish/linseed oil	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000018	0,00000000019	0,00000000020	0,00000000026	0,00000000026	p
Input hydraulic excavator in waste sorting of varnish	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input hydraulic excavator in waste sorting of linseed oil	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,002	0,002	0,002	0,003	0,003	m³
Input electricity in waste sorting of epoxy resin	Electricity, low voltage (BE) market for electricity, low voltage Cut-off, S	0,001	0,001	0,001	0,001	0,001	kWh
Input hydraulic excavator in waste sorting of epoxy resin	Excavation, hydraulic digger (RER) excavation, hydraulic digger Cut-off, S	0,0003	0,0004	0,0004	0,0005	0,0005	m³
Input sorting facility in waste sorting of epoxy resin	Sorting facility, for construction waste (GLO) market for sorting facility, for construction waste Cut-off, S	0,00000000004	0,00000000004	0,00000000004	0,00000000006	0,00000000006	p
Landfill of waterproof cover	KG_Waste polyethylene (CH) treatment of waste polyethylene, sanitary landfill Cut-off, S	0,160	0,172	0,184	0,232	0,238	kg
Incineration of waterproof cover	KG_Waste polyethylene (CH) treatment of waste polyethylene, municipal incineration FAE Cut-off, S	1,359	1,464	1,568	1,969	2,021	kg
Incineration paint/varnish/linseed oil	KG_Waste paint (CH) treatment of waste paint, municipal incineration FAE Cut-off, S	1,776	1,913	2,050	2,574	2,642	kg
Incineration of epoxy resin	KG_Hazardous waste, for incineration (Europe without Switzerland) treatment of hazardous waste, hazardous waste incineration Cut-off, S	0,385	0,415	0,444	0,558	0,573	kg

Note: The reuse scenarios and associated reclamation processes are based on the case studies reported by Feys & Defever (2025). The presented values were recalculated and proportionally scaled by weight according to the species-specific densities applied in this study. Processes indicated in light grey were excluded from the calculations due to their project-specific nature.

Appendix E: Assumptions derived from “Environmental Profile of Buildings” (TOTEM Methodology)

Table 1. Default scenarios for the transport of building materials from factory to building site (OVAM et al., 2023)

Product group/ Material category	Transport route		Means of transport from							Average transport distance from		
	% directly from factory to site	% via an inter- mediary supplier	factory to site			factory to supplier	supplier to site			factory to site [km]	factory to supplier [km]	supplier to site [km]
			Lorry 16-32 ton (EURO 5)	Lorry 75-16 ton (EURO 5)	Lorry 35-75 ton (EURO 5)	Lorry >32 ton (EURO 5)	Lorry 16-32 ton (EURO 5)	Lorry 75-16 ton (EURO 5)	Lorry 35-75 ton (EURO 5)			
Bulk materials for structural work (e.g. cement, sand, gravel, ...)	75%	25%	100%	0%	0%	100%	90%	10%	0%	100	100	35
Poured concrete	100%	0%	100%	0%	0%	n/a	n/a	n/a	n/a	100	100	35
Prefabricated products for structural work (e.g. beams, columns, ...)	100%	0%	100%	0%	0%	100%	100%	0%	0%	100	100	35
Loose products (e.g. blocks, bricks, roof tiles, plasterboard, ...)	40%	60%	100%	0%	0%	100%	85%	15%	0%	100	100	35
Insulation	40%	60%	100%	0%	0%	100%	85%	15%	0%	100	100	35
Finishing products: floor coverings (e.g. carpet, linoleum, ceramic tiles, ...)	10%	90%	90%	10%	0%	100%	90%	10%	0%	100	100	35
Finishing products: plasters (e.g. gypsum plaster, external plaster, ...)	40%	60%	50%	50%	0%	100%	50%	50%	0%	100	100	35
Finishing products: cabinet work (e.g. window frames, stairs, ...)	90%	10%	50%	45%	5%	100%	40%	50%	10%	100	100	35
Finishing products: paints and varnishes	10%	90%	0%	100%	0%	100%	0%	80%	20%	100	100	35
Installations (e.g. heating boiler, radiators, ventilation, ...)	0%	100%	n/a	n/a	n/a	100%	0%	80%	20%	100	100	35

Table 2. Waste scenarios for the 37 waste categories considered in the B-PCR (OVAM et al., 2023)

Main category	Waste category	Landfill	Incineration ^a	Reuse	Recycling	Sorted on building site ^a
Stony & glass	Bricks, roof tiles	5%	0%	0%	95%	75%
	Bulk materials (e.g. sand, gravel, expanded clay grains)	5%	0%	95%	0%	90%
	Concrete	5%	0%	0%	95%	75%
	Flat glass	5%	0%	0%	95%	70%
	Other stony waste (e.g. tiles, natural stone, slates, sand-lime blocks)	5%	0%	0%	95%	75%
	Porcelain and ceramics (e.g. toilet, bath, washbasin)	15%	0%	0%	85%	75%
Wood	Chemically treated, impregnated wood (e.g. railway sleepers, wood used for carports, outdoor playsets, garden screens)	0%	100%	0%	0%	40%
	Composite wood products (e.g. fibreboards (like plywood, chipboard, OSB, MDF), veneer, laminate)	0%	95%	0%	5%	40%
	Surface treated, solid wood (e.g. painted or varnished (like window frames, solid parquet))	0%	85%	0%	15%	40%
	Untreated, uncontaminated wood (e.g. roofs, structures, formworks, auxiliary timber)	0%	25%	0%	75%	40%
Metals	Metals: iron, steel, non-ferro (copper, brass, aluminium, lead, zinc, tin)	5%	0%	0%	95%	85%
Packaging (on construction site) ^c	EPS packaging	10%	30%	0%	60%	50%
	Pallets	0%	40%	20%	40%	50%
	Paper and cardboard packaging	0%	5%	0%	95%	50%
	Plastic films packaging	5%	60%	0%	35%	50%
Insulation materials	Mineral insulation materials (e.g. stone wool, glass wool)	50%	50%	0%	0%	0%
	Organic insulation materials (e.g. vegetable fibres (like wood, coconut, hemp, flax), cellulose (in bulk or blankets), sheep wool, cork (in bulk or boards))	5%	95%	0%	0%	0%
	Synthetic insulation materials (e.g. polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), phenolic foam, expanded polystyrene (EPS))	5%	95%	0%	0%	0%
Fibre cement products	Fibre cement products (e.g. fibre cement slabs or slates)	100%	0%	0%	0%	75%

Table 3. Waste scenarios for the 37 waste categories considered in MMG based on the B-PCR (OVAM et al., 2023)

Main category	Waste category	Landfill	Incineration ^a	Reuse	Recycling	Sorted on building site ^a
Gypsum elements	Gypsum elements (e.g. gypsum blocks, gypsum (fibre/plaster)boards)	80%	0%	0%	20%	50%
Aerated / cellular concrete	Aerated autoclaved concrete (e.g. elements, blocks)	70%	0%	0%	30%	30%
Bitumen	Bitumen (e.g. bituminous roofing, vapour barrier, waterproofing membrane)	85%	5%	0%	10%	0%
Polyolefins (PP, PE)	Polyolefins (PP, PE) (e.g. kraft paper or polyethylene (PE) vapour barrier, ducts), excluding packaging	10%	85%	0%	5%	0%
Elastomers	Elastomers (e.g. EPDM roofing)	90%	0%	0%	10%	0%
PVC	PVC cabling (e.g. electric cables and wire insulation)	10%	40%	0%	50%	0%
	PVC pipes (e.g. for sewerage) ²	10%	30%	0%	50%	0%
	PVC profiles (e.g. window frames)	10%	45%	0%	45%	0%
	PVC sheets (e.g. PVC roofing, waterproofing membranes (like for swimming pools))	20%	65%	0%	15%	0%
Supple flooring	Supple flooring (e.g. linoleum, fixed carpet, vinyl)	0%	95%	0%	5%	0%
Finishing layers ^d	Finishing layer fixed to stony waste (e.g. plaster (like gypsum plaster, calcareous plaster, loam plaster), paint, coatings, adhesives)	5%	0%	0%	95% ^a	0%
	Finishing layer fixed to wood, plastic or metal (e.g. paint, coatings, adhesives)	0%	100% ^d	0%	0%	0%
Remaining waste	Combustible remaining waste	0%	100%	0%	0%	0%
	Non-combustible remaining waste	100%	0%	0%	0%	75%
Other hazardous waste	Aerosols and kits (e.g. PU foam, silicones)	0%	100%	0%	0%	100%
	Asbestos (bounded, unbounded)	100%	0%	0%	0%	100%
	Fluorescent lamps	30%	0%	0%	70%	100%
	Liquid construction site waste (e.g. paints, adhesives, resins, form mould oil, white spirit)	0%	75%	0%	25%	100%

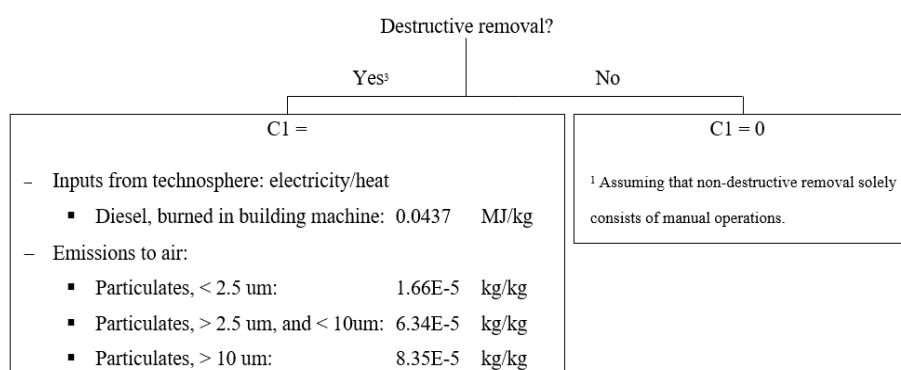


Figure 1. Assumptions for Module C1 (OVAM et al., 2023)

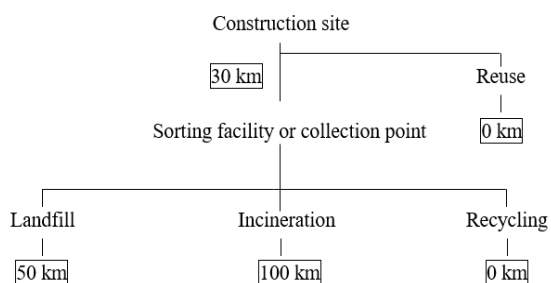


Figure 2. Assumptions for transport distances within Module C2 (OVAM et al., 2023)

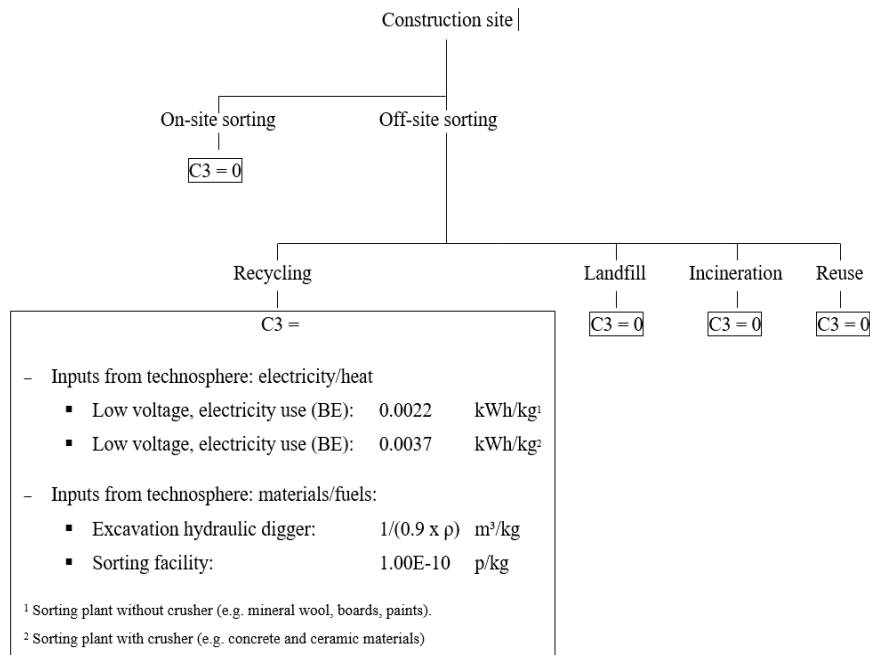


Figure 3. Assumptions for Module C3 (OVAM et al., 2023)

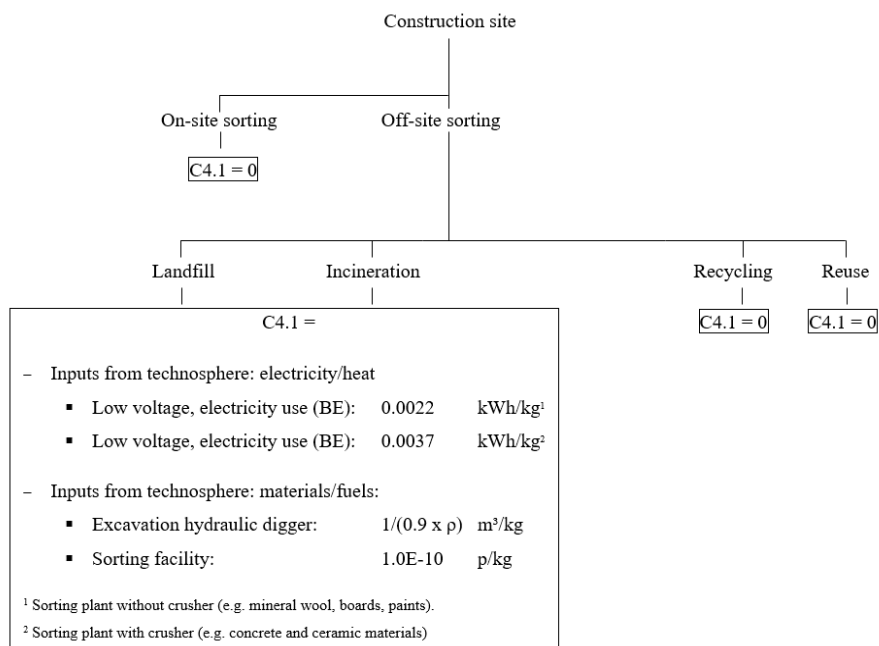


Figure 4. Assumptions for Module C4 (OVAM et al., 2023) μ

Appendix F: Additional allocation method results for pine, larch, oak, and beech

Note: The results for spruce are discussed in sections 1.4 and 1.5 of the main text. This Appendix presents the corresponding allocation method results for pine, larch, oak, and beech. The five allocation methods for the growth approach are presented first, followed by the three allocation methods for the regrowth approach. The influence of fossil and biogenic carbon emissions is discussed in sections 1.2 and 1.3.

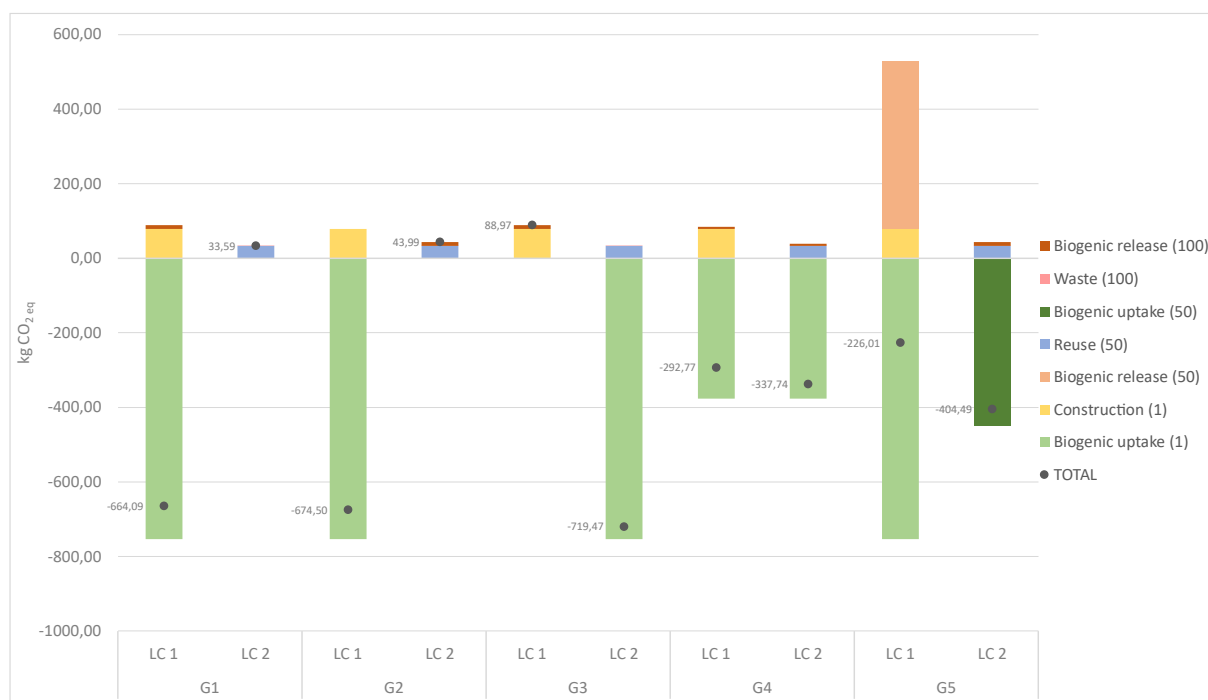


Figure 1. Comparison of allocation methods for pine under the growth approach

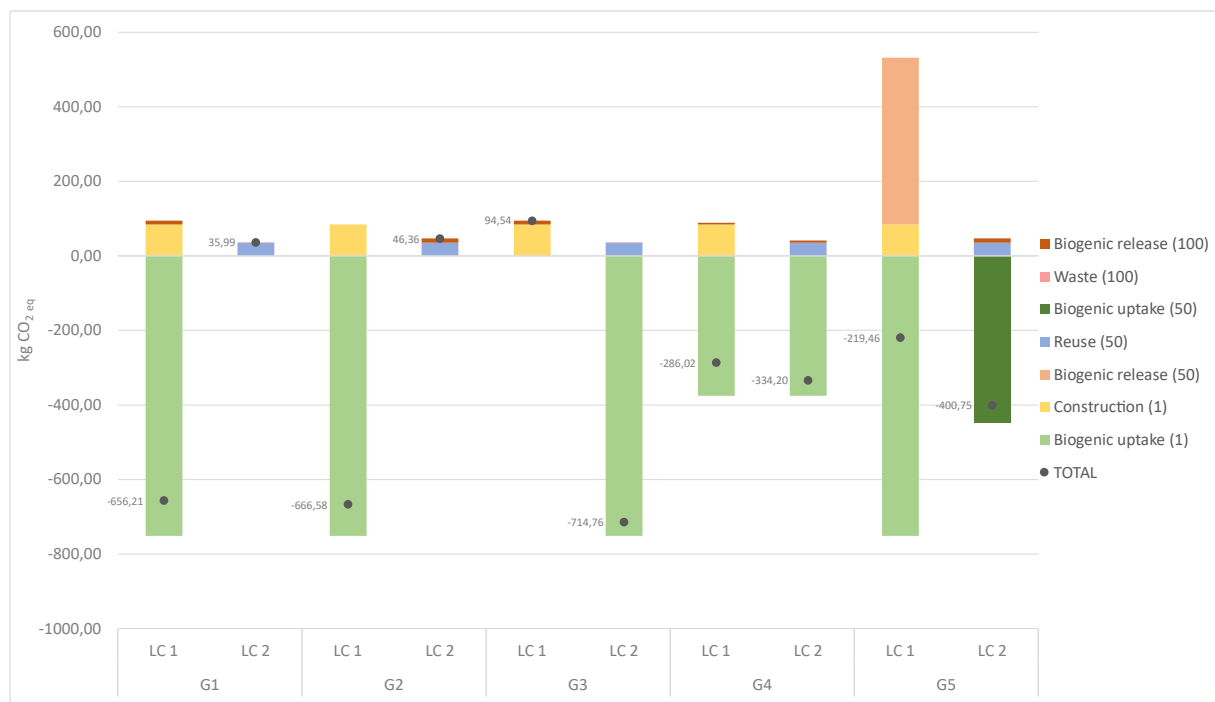


Figure 2. Comparison of allocation methods for larch under the growth approach



Figure 3. Comparison of allocation methods for oak under the growth approach

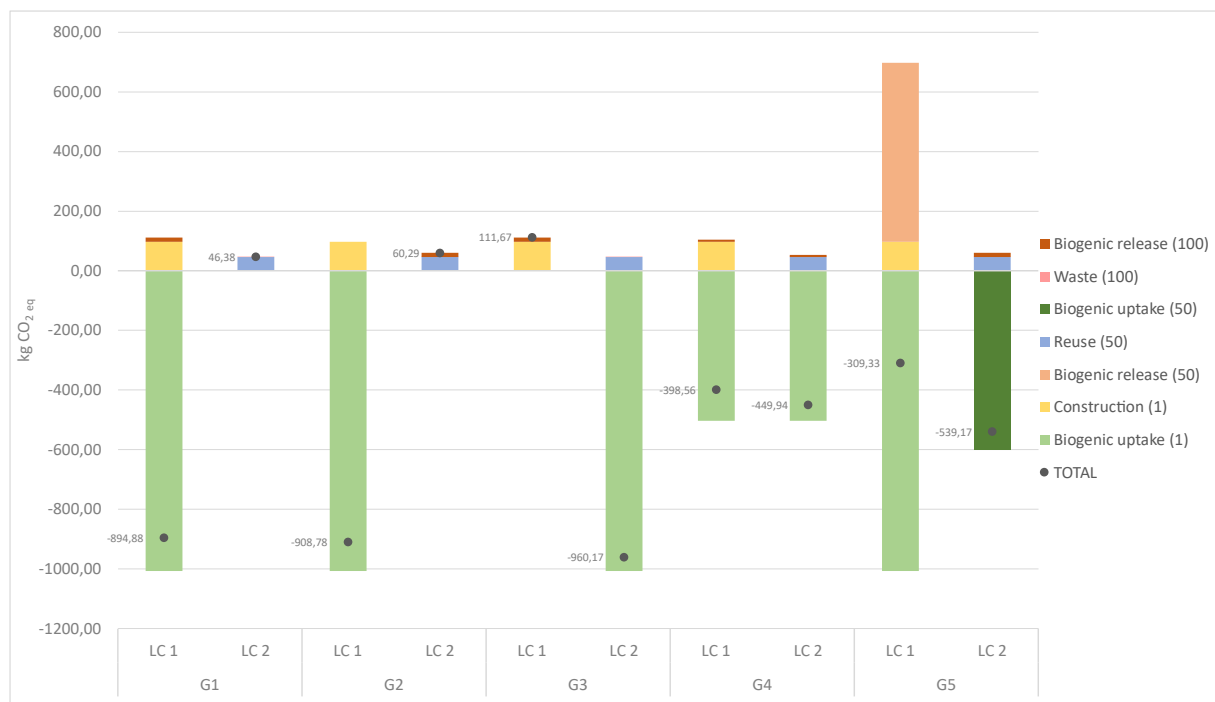


Figure 4. Comparison of allocation methods for beech under the growth approach

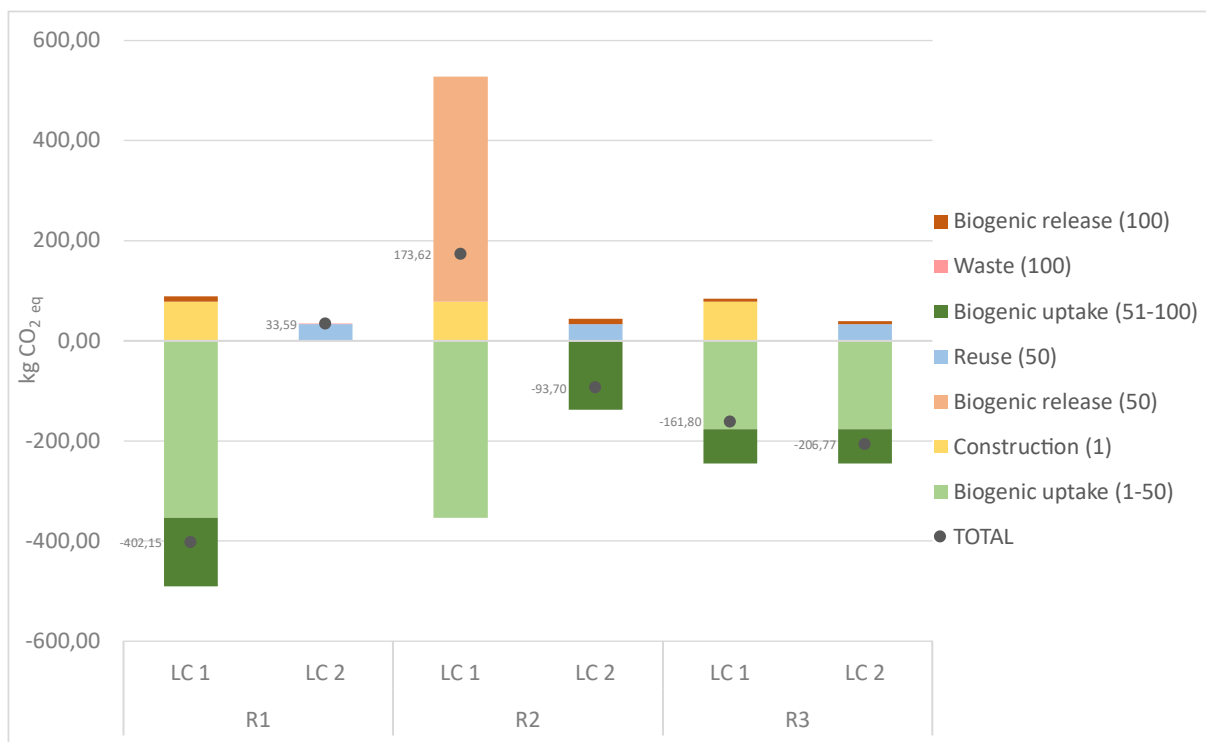


Figure 5. Comparison of allocation methods for pine under the regrowth approach

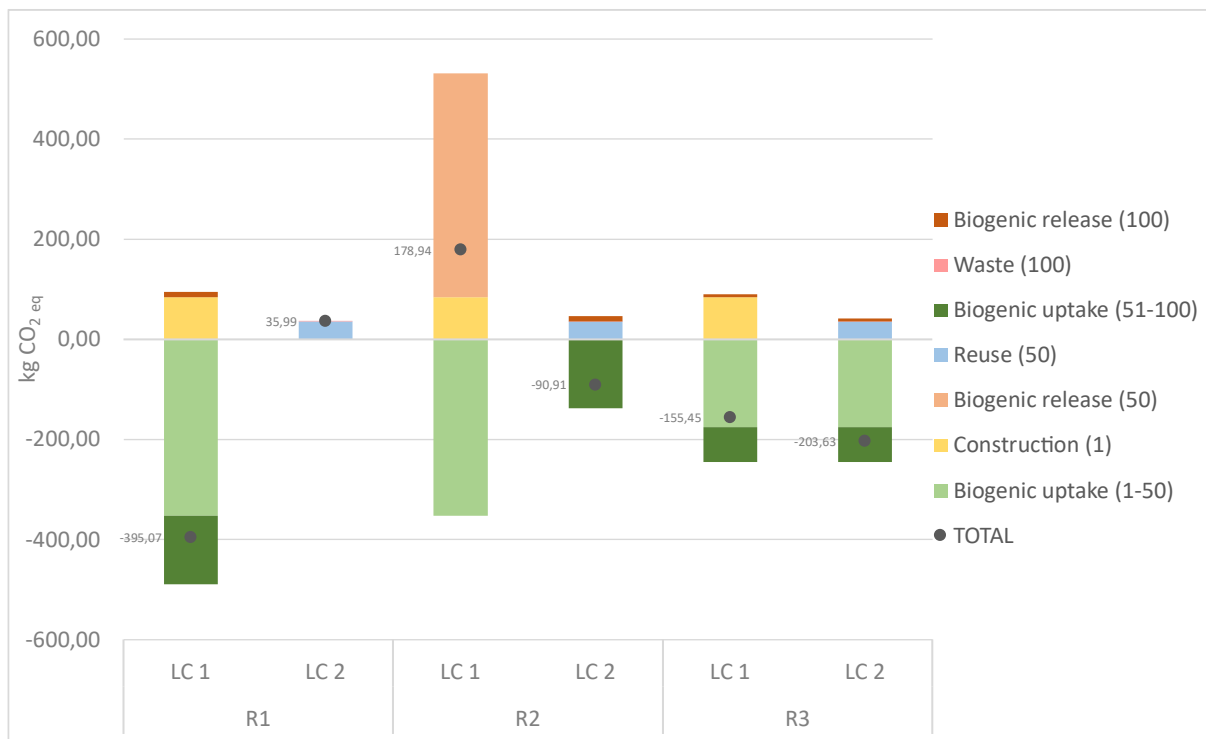


Figure 6. Comparison of allocation methods for larch under the regrowth approach

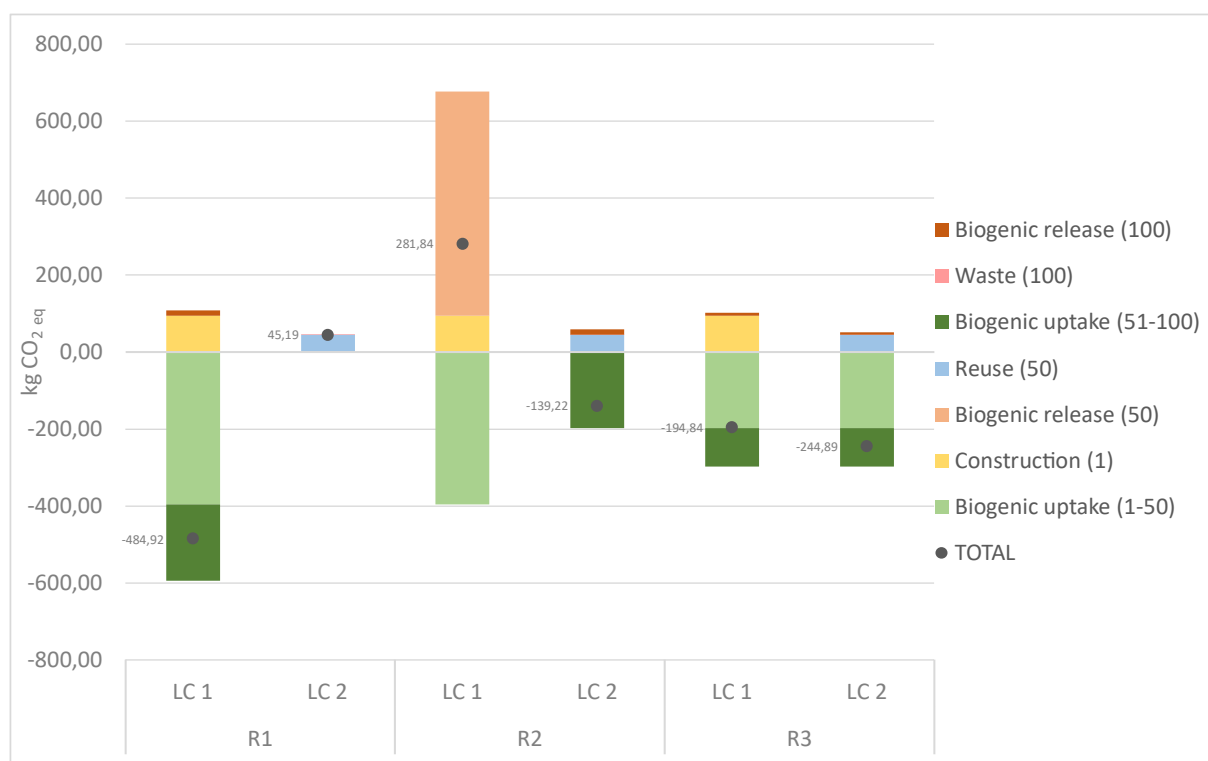


Figure 7. Comparison of allocation methods for oak under the regrowth approach

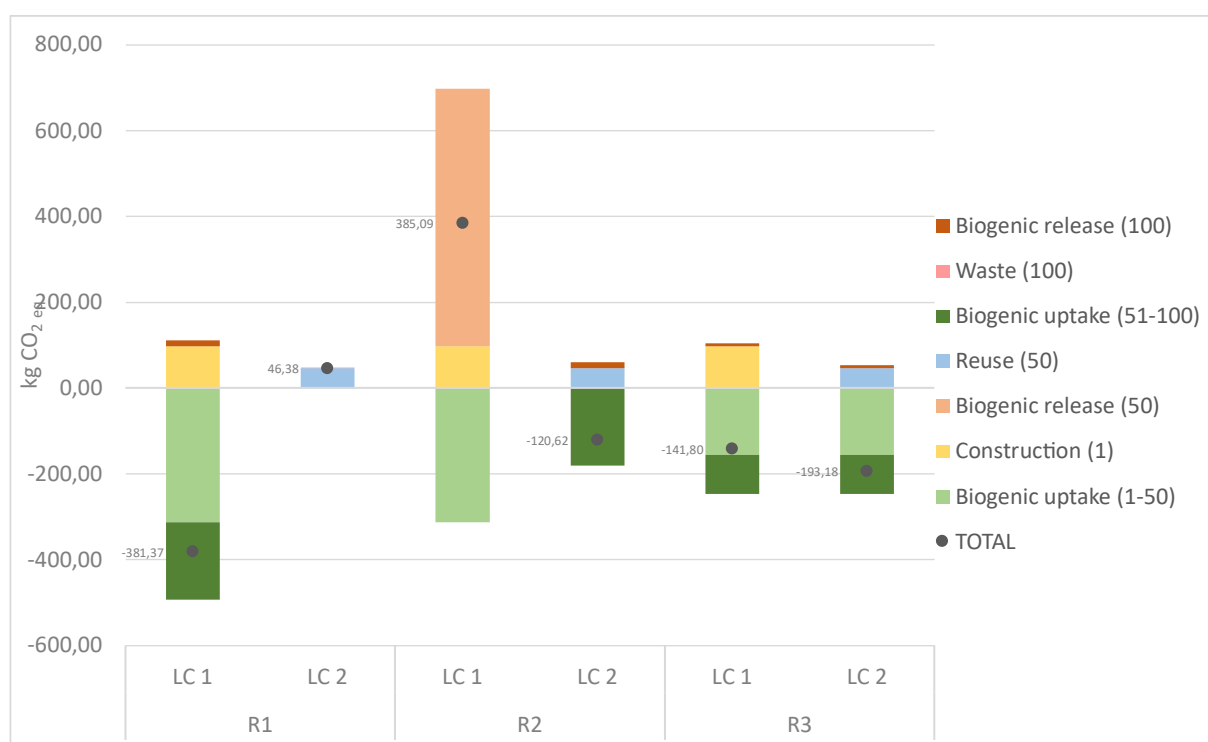


Figure 8. Comparison of allocation methods for beech under the regrowth approach

Appendix G: Additional density sensitivity results

Note: The impact of density on fossil emissions related to production and reuse processes is discussed in section 2.2, while the influence on biogenic carbon emissions is discussed in section 2.3. The impact of density on end-of-life processes is presented in this Appendix. In addition, this Appendix presents the influence of density for the remaining allocation methods. The results for allocation methods G1, G5, and R2 are discussed in sections 2.4 and 2.5.

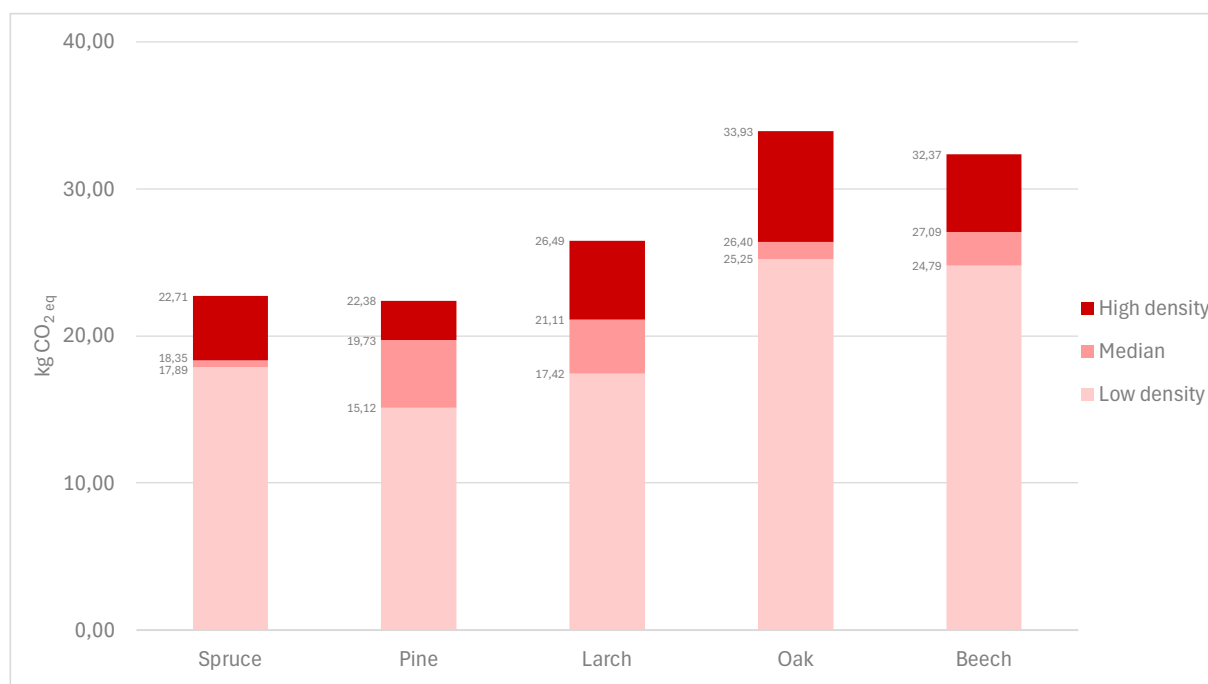


Figure 1. Influence of density variation on the end-of-life processes

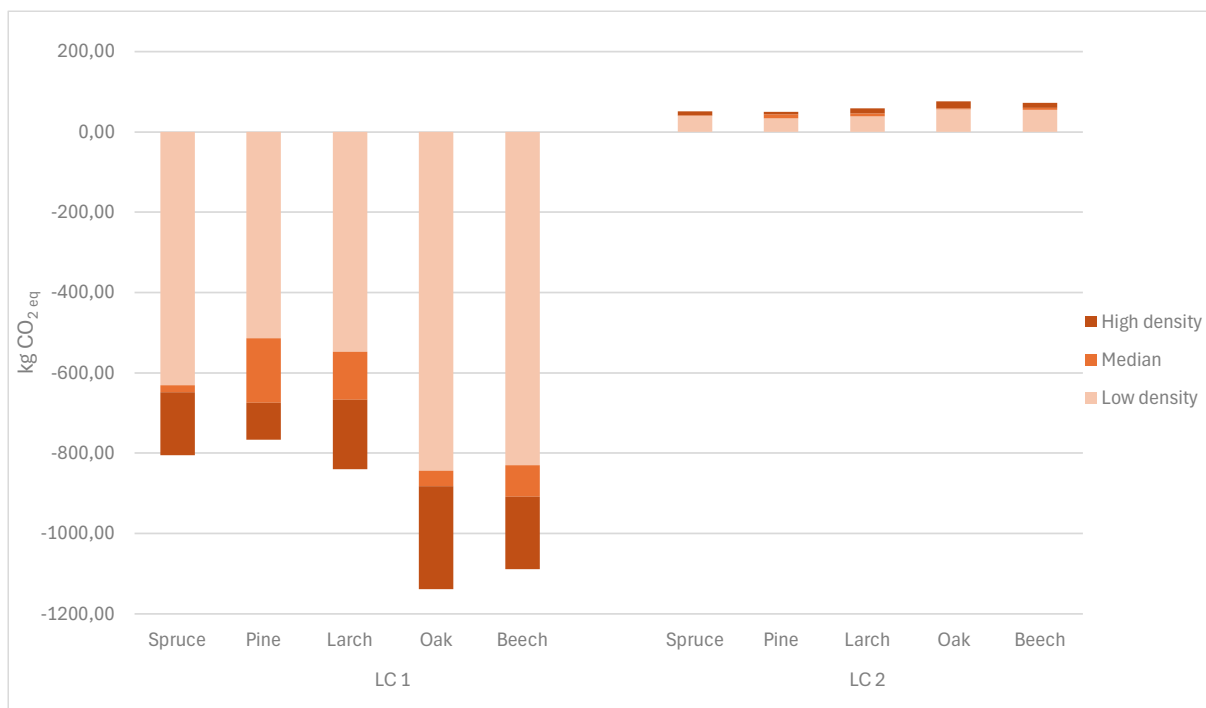


Figure 2. Impact of density variation for allocation method G2

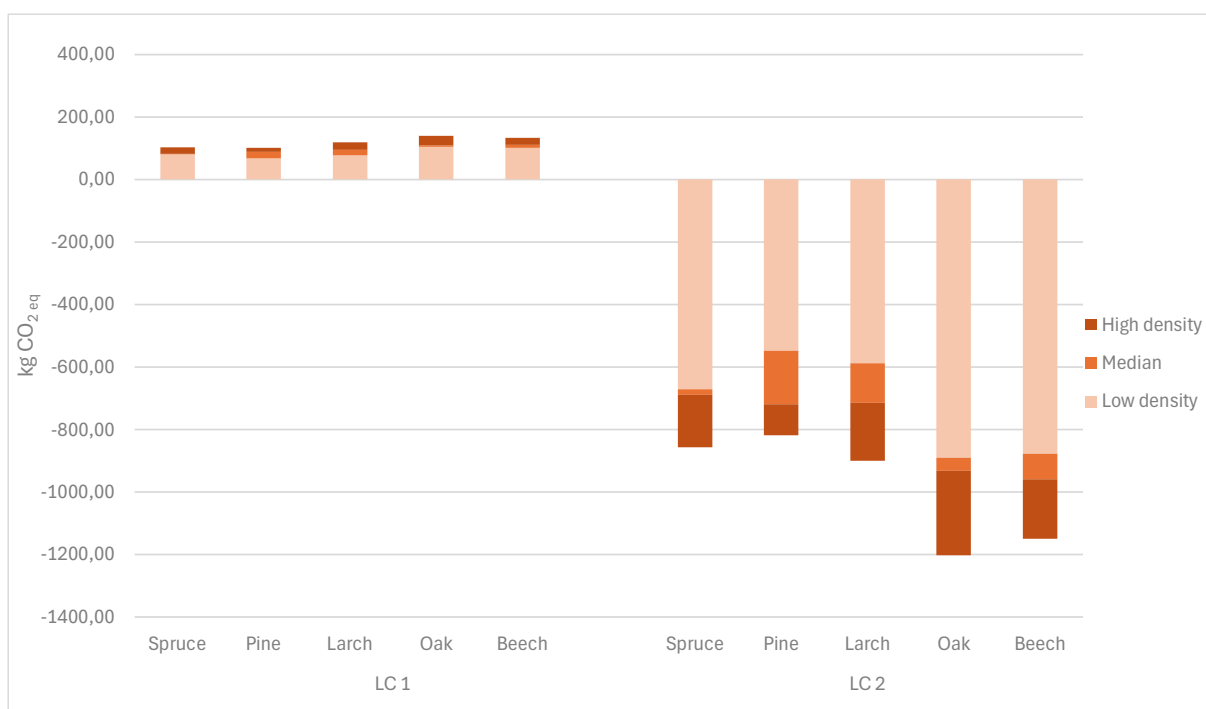


Figure 3. Impact of density variation for allocation method G3

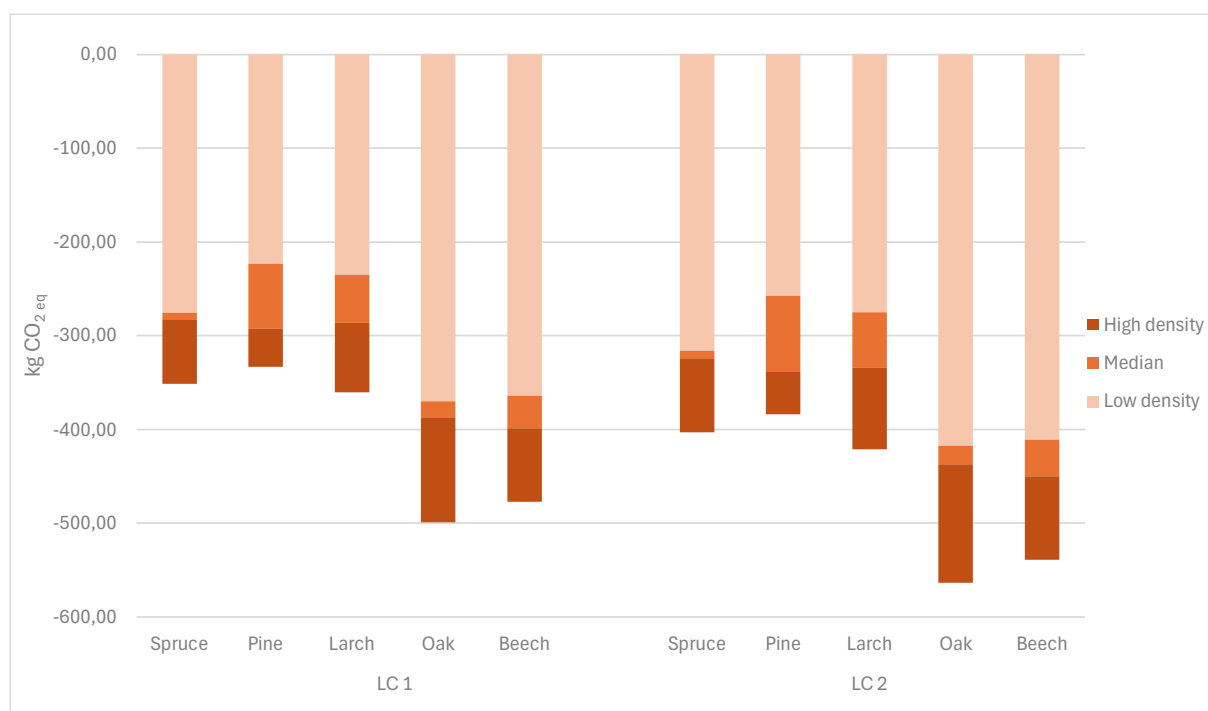


Figure 4. Impact of density variation for allocation method G4

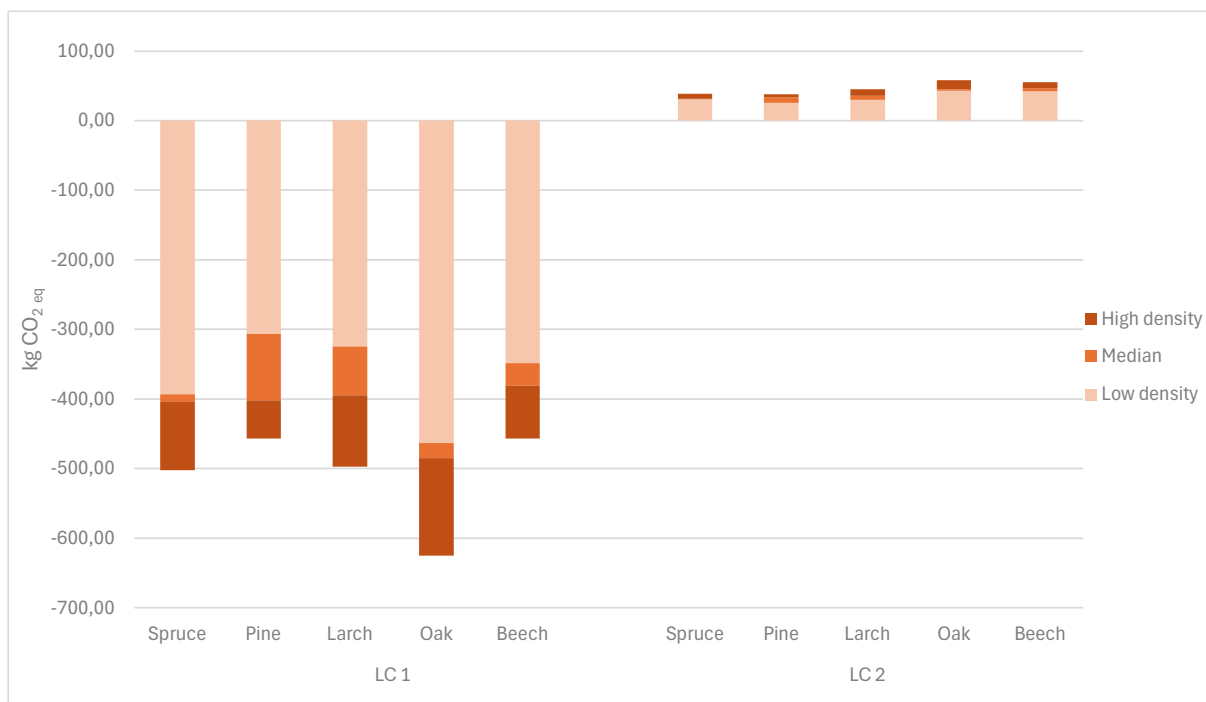


Figure 5. Impact of density variation for allocation method R1

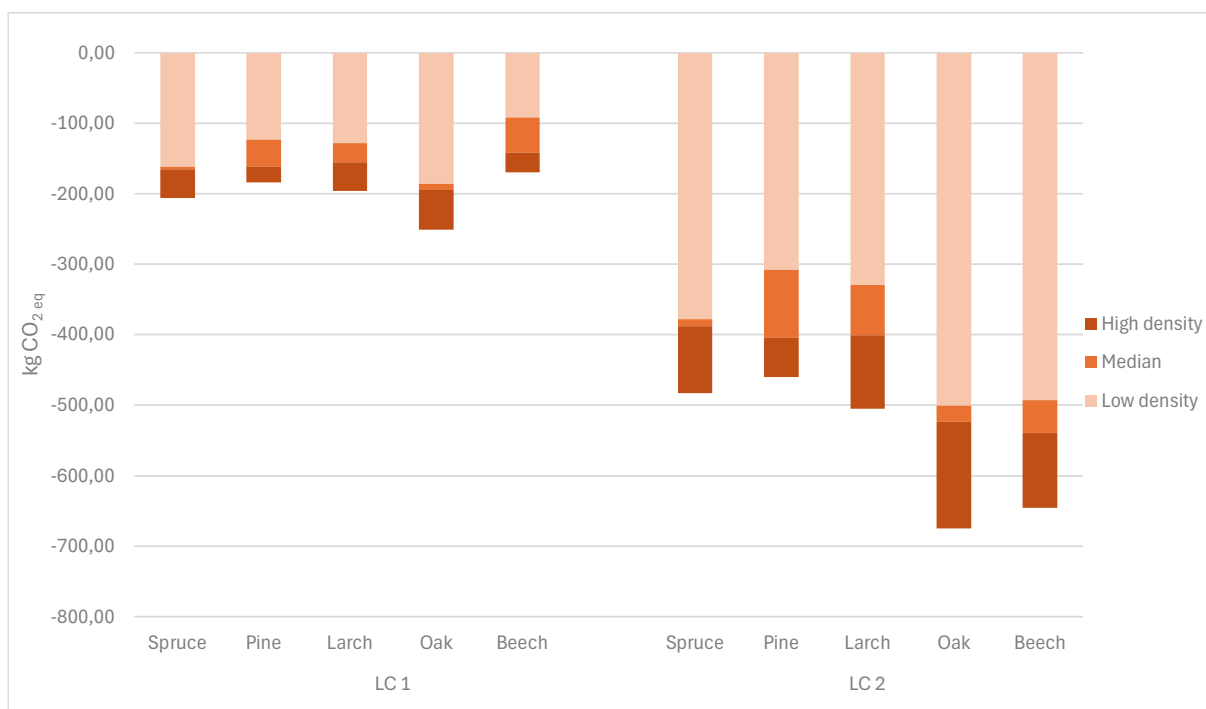


Figure 6. Impact of density variation for allocation method R3

Appendix H: Additional rotation period sensitivity results

Note: This Appendix first presents the growth curves and corresponding yearly biogenic carbon uptake for the selected wood species and rotation period scenarios. The cumulative biogenic carbon uptake over time is discussed in Section 3.1. Subsequently, the results for allocation methods R1 and R3 are presented in this Appendix, while the results for allocation method R2 are discussed in Section 3.3.

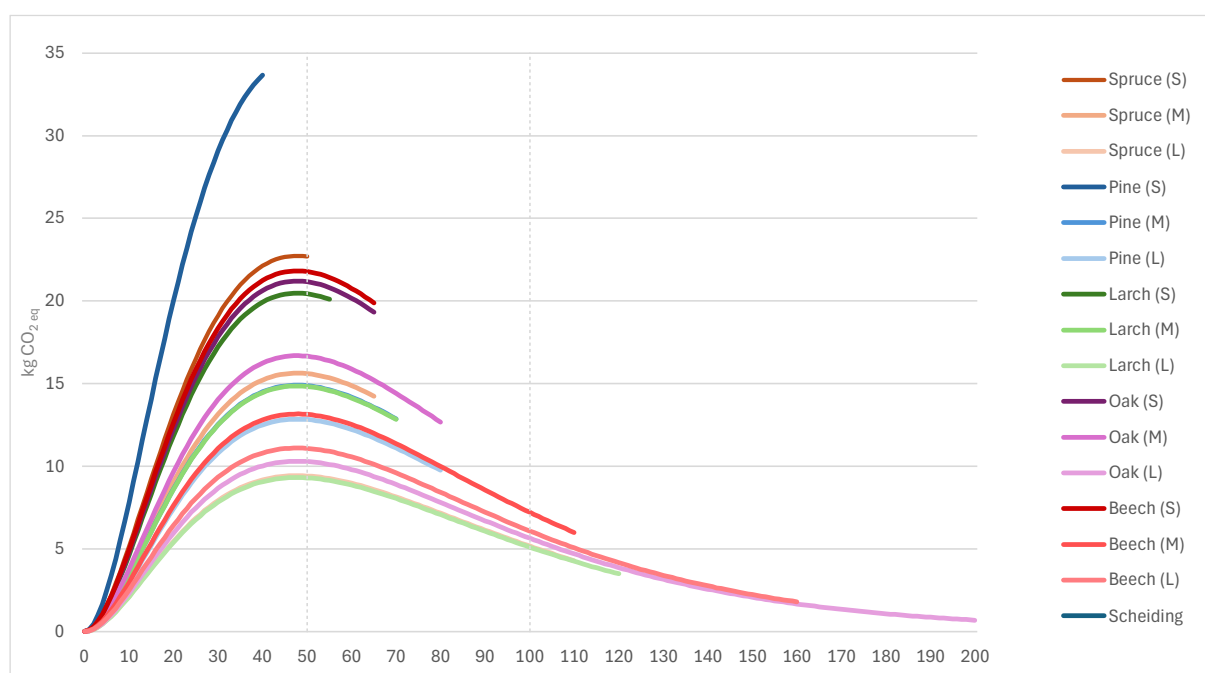


Figure 1. Yearly biogenic carbon uptake for the selected wood species and rotation period scenarios

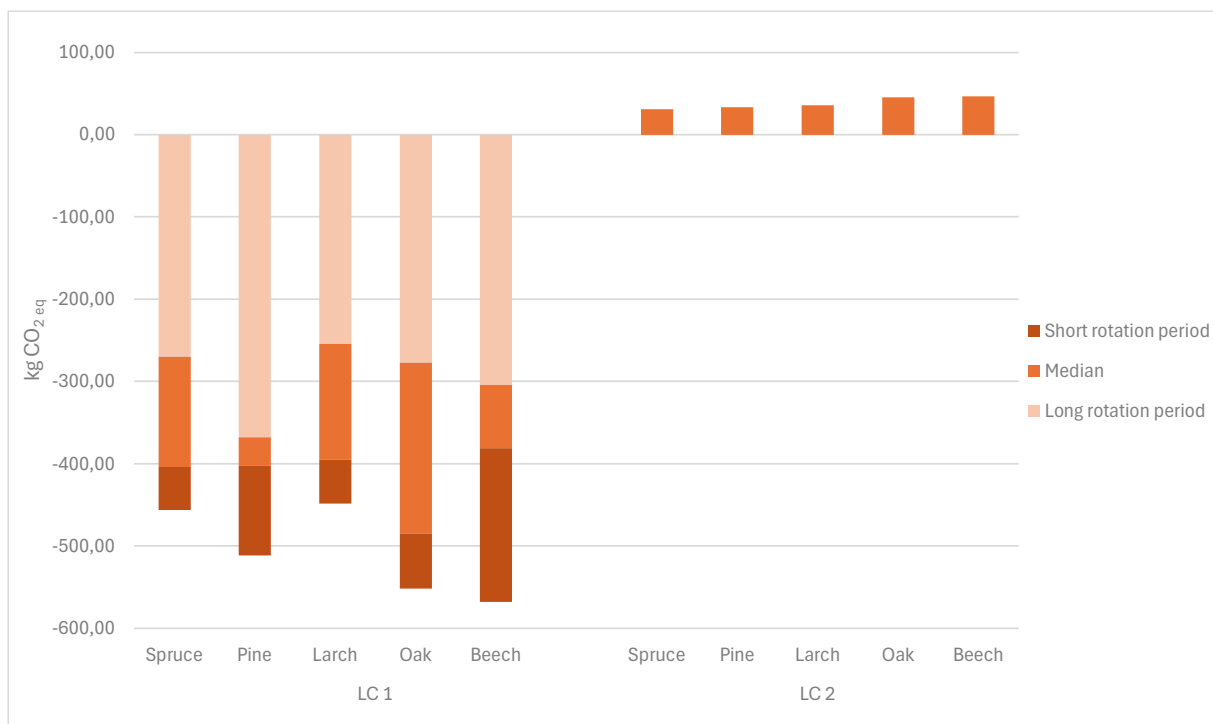


Figure 2. Impact of rotation period variation for allocation method R1

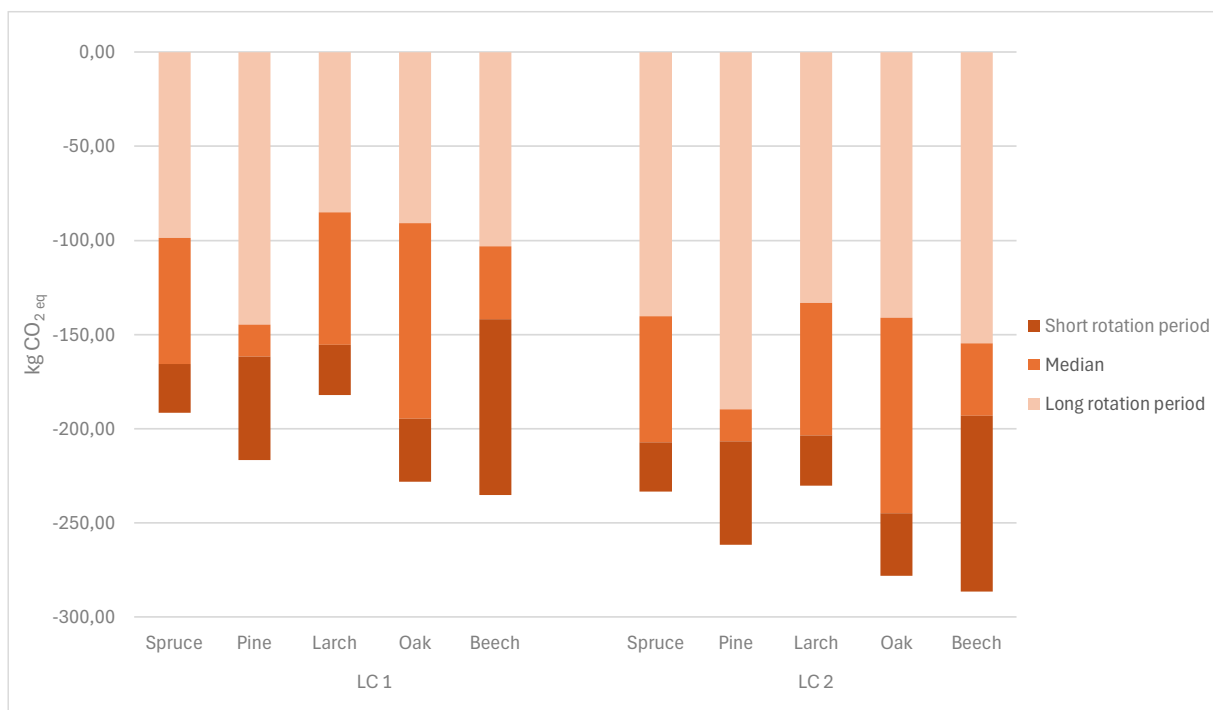


Figure 3. Impact of rotation period variation for allocation method R3

Appendix I: Additional reuse scenario sensitivity results

Note: This Appendix presents the results for the additional allocation methods related to the reuse scenario sensitivity analysis. The results for allocation methods G1 and R1, which show identical impacts, are discussed in Section 4.2. The results for allocation methods G5 and R2 are discussed in Section 4.3.

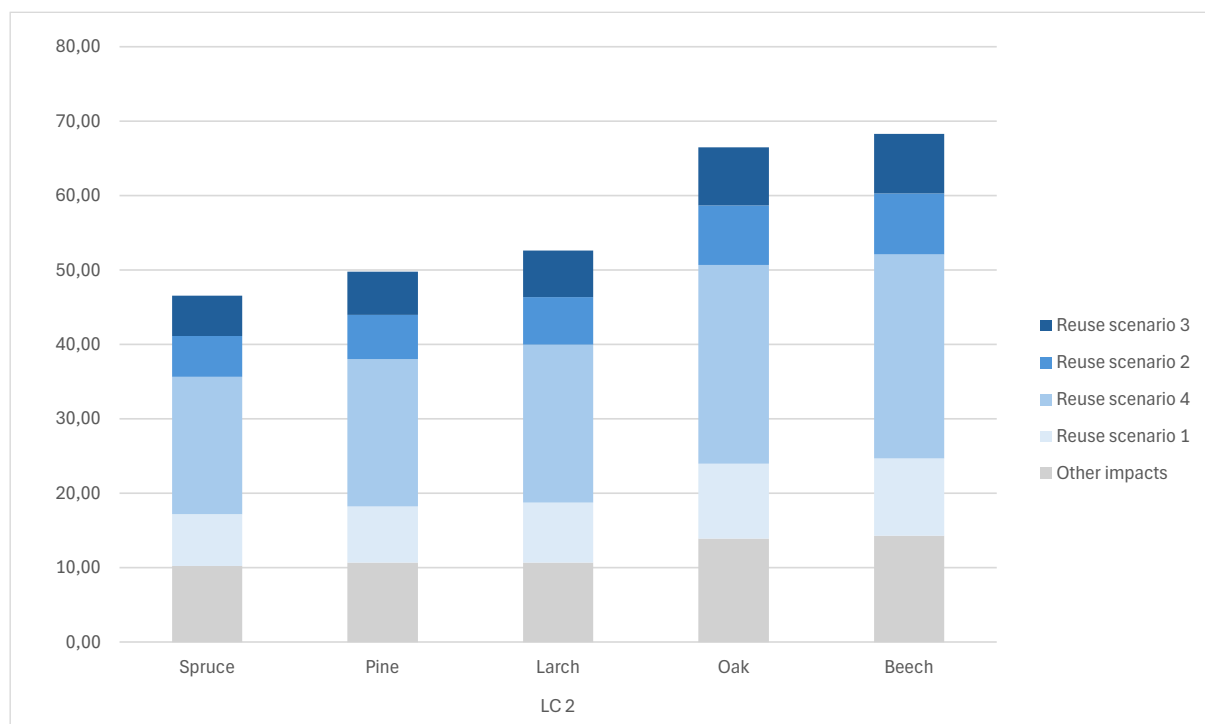


Figure 1. Impact of reuse scenario variation for allocation methods G2

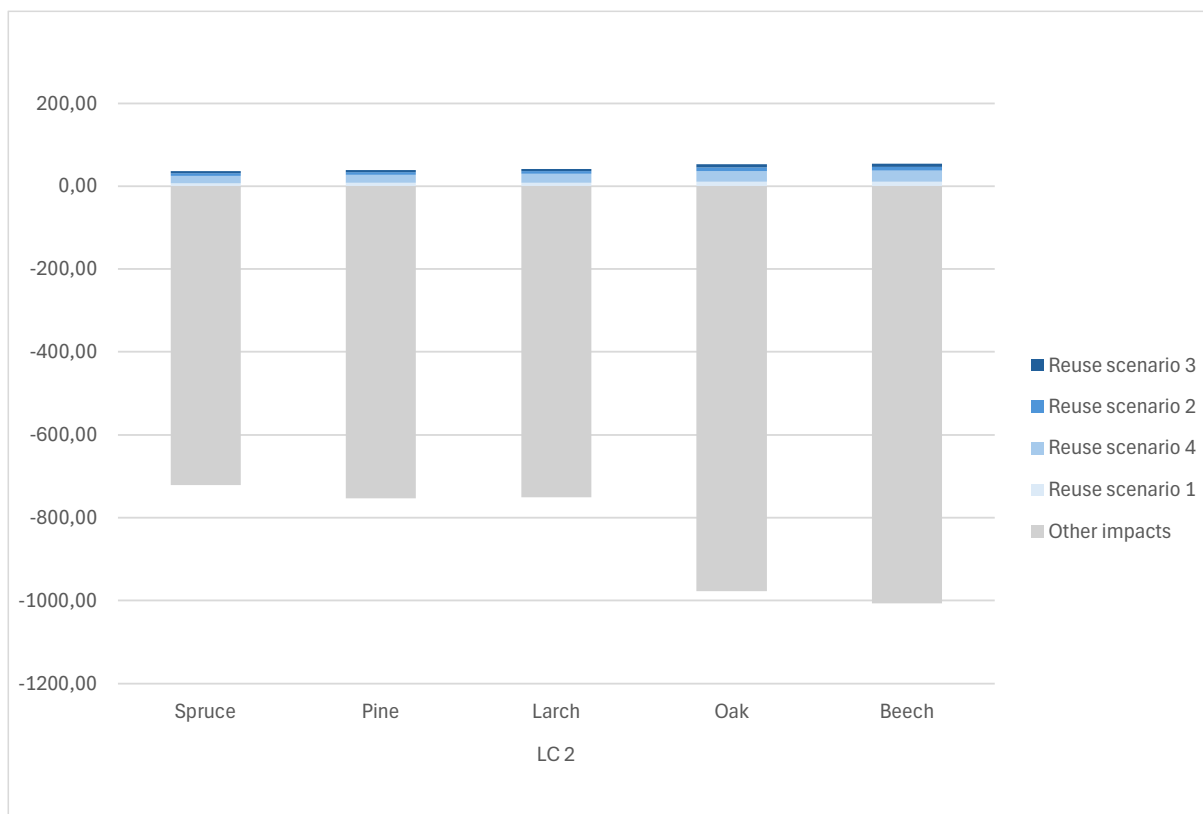


Figure 2. Impact of reuse scenario variation for allocation methods G3

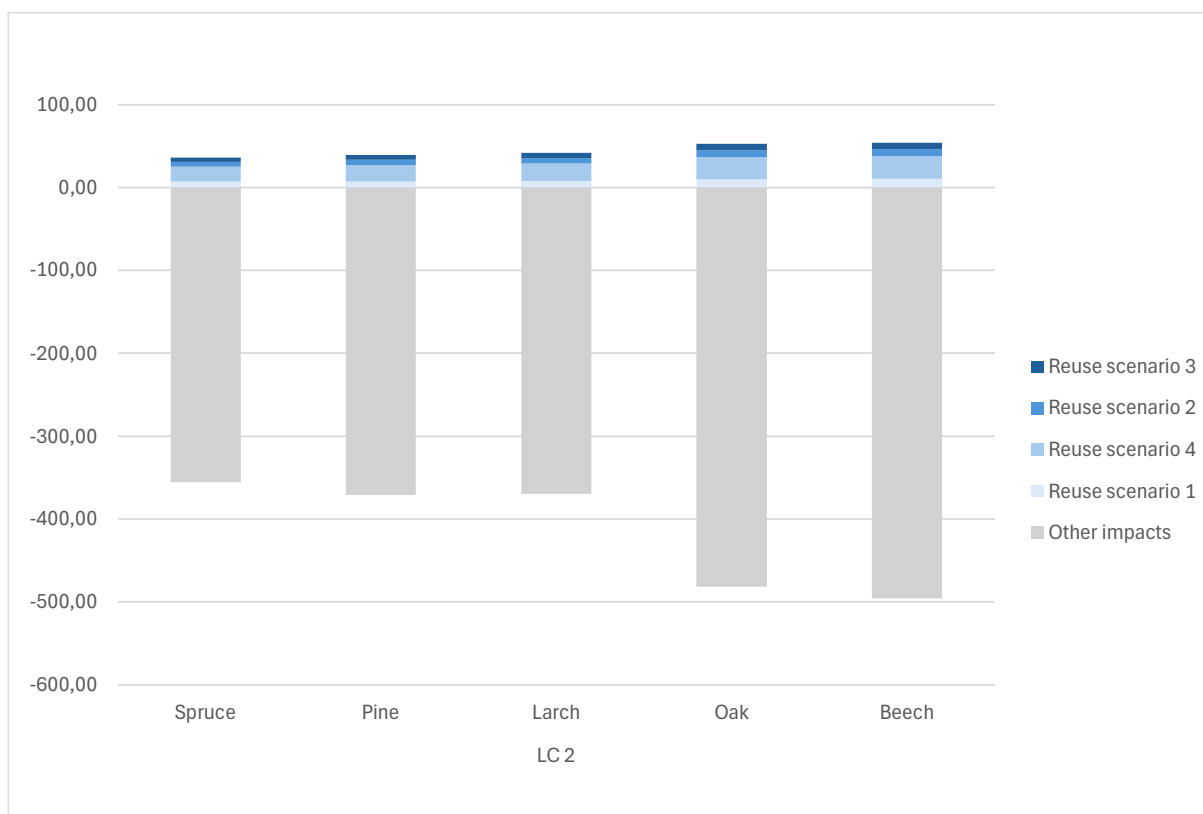


Figure 3. Impact of reuse scenario variation for allocation methods G4

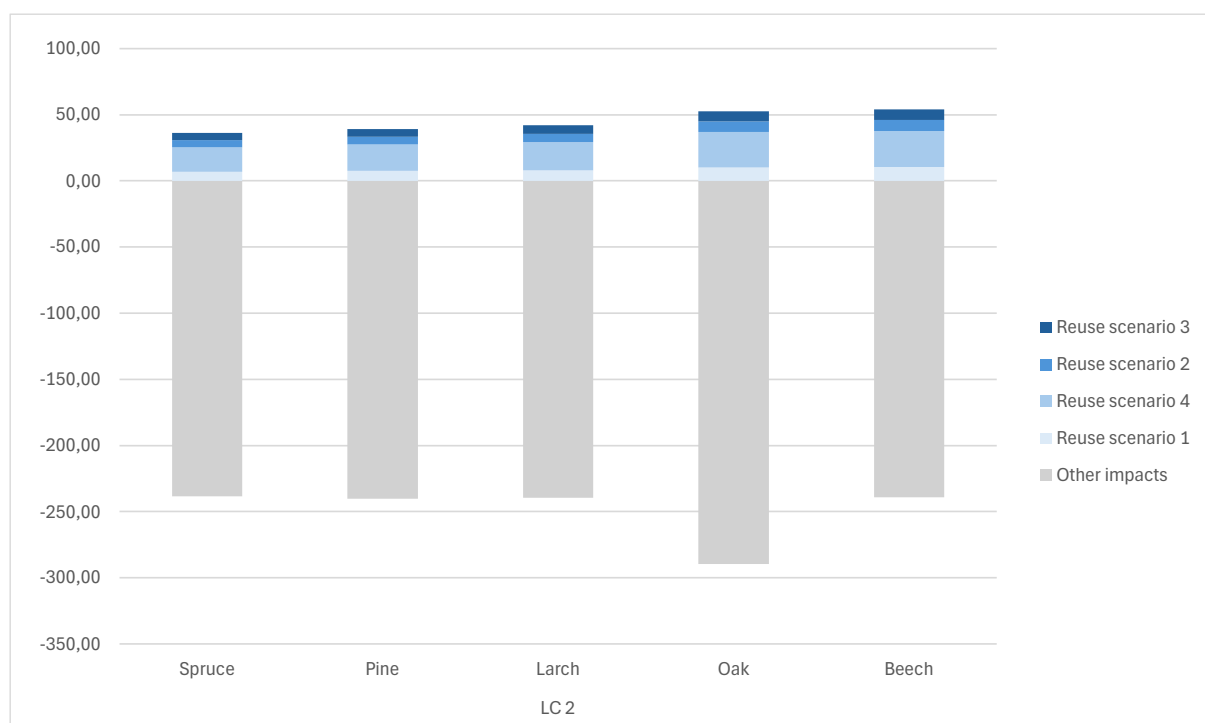


Figure 4. Impact of reuse scenario variation for allocation methods R3

Appendix J: Additional service life sensitivity results

Note: This Appendix presents the influence of different service life assumptions on end-of-life processes. The impact on reuse processes is discussed in section 5.2, while the influence on biogenic carbon uptake and release is discussed in section 5.3. Subsequently, this Appendix presents the results for the remaining allocation methods. The results for allocation methods G1 and R1 are discussed in section 5.4, while the results for allocation methods G5 and R2 are discussed in section 5.5.

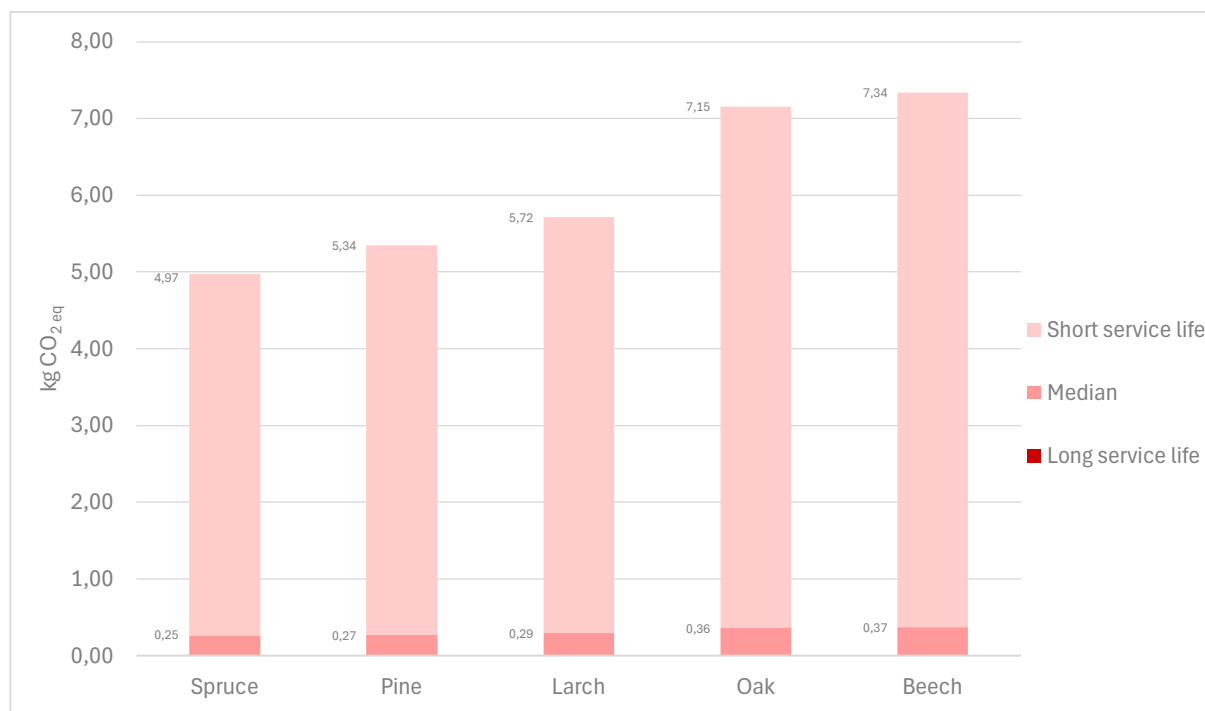


Figure 1. Fossil carbon emissions associated with end-of-life processes for different service life values

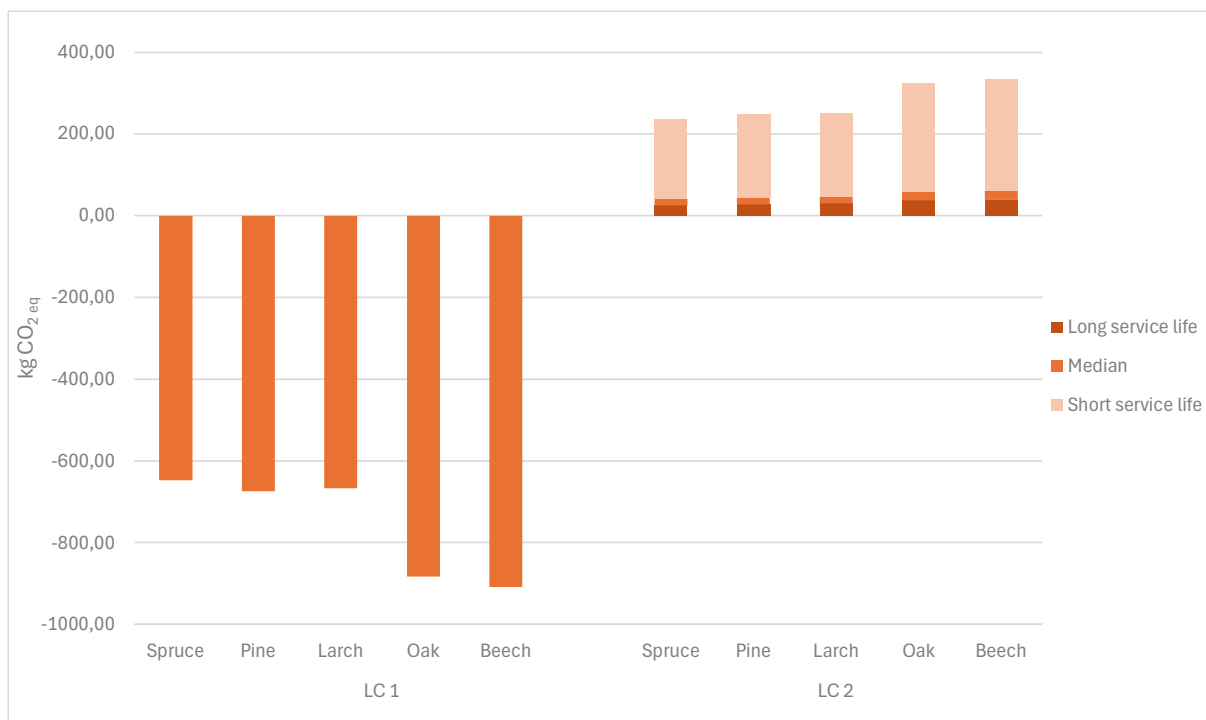


Figure 2. Impact of service life variation for allocation method G2

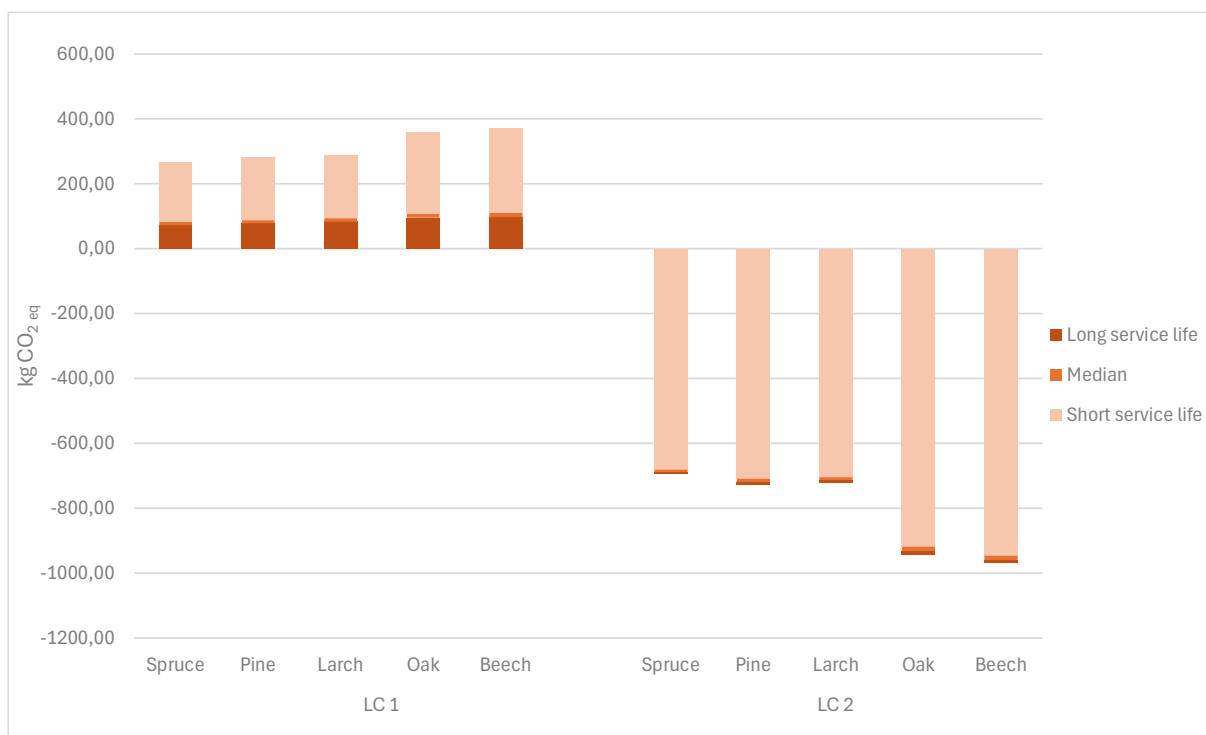


Figure 3. Impact of service life variation for allocation method G3

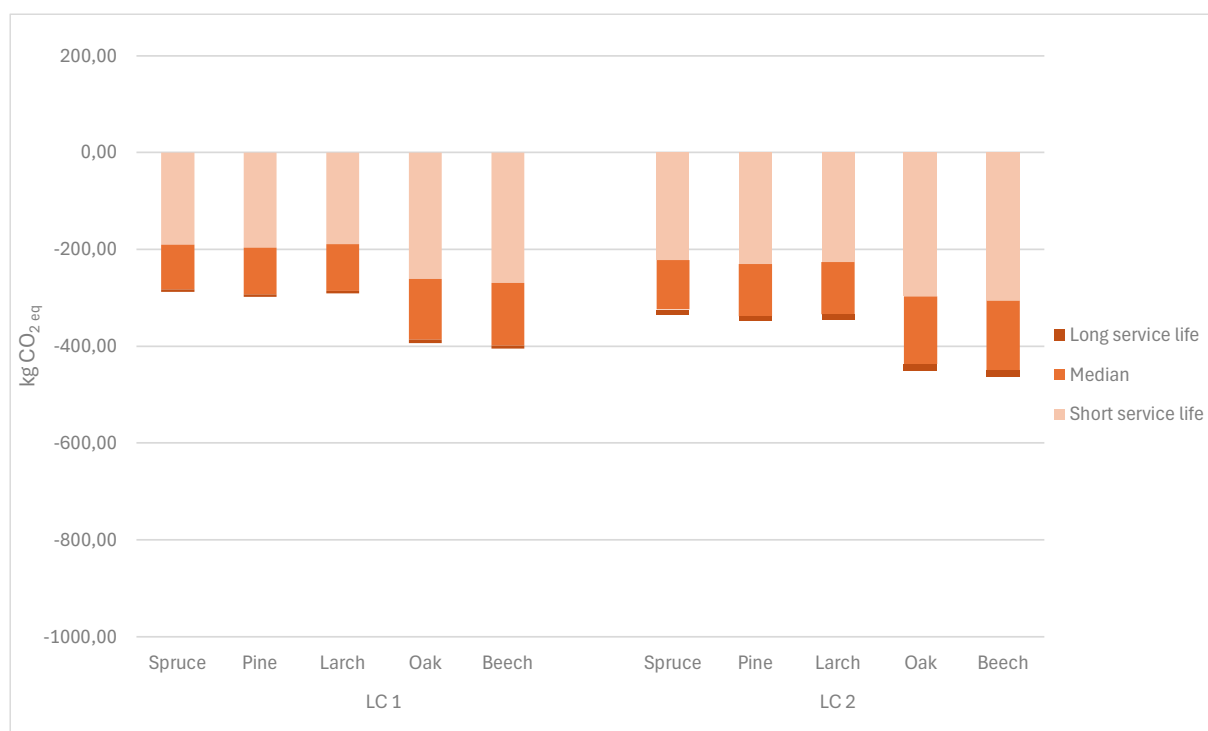


Figure 4. Impact of service life variation for allocation method G4

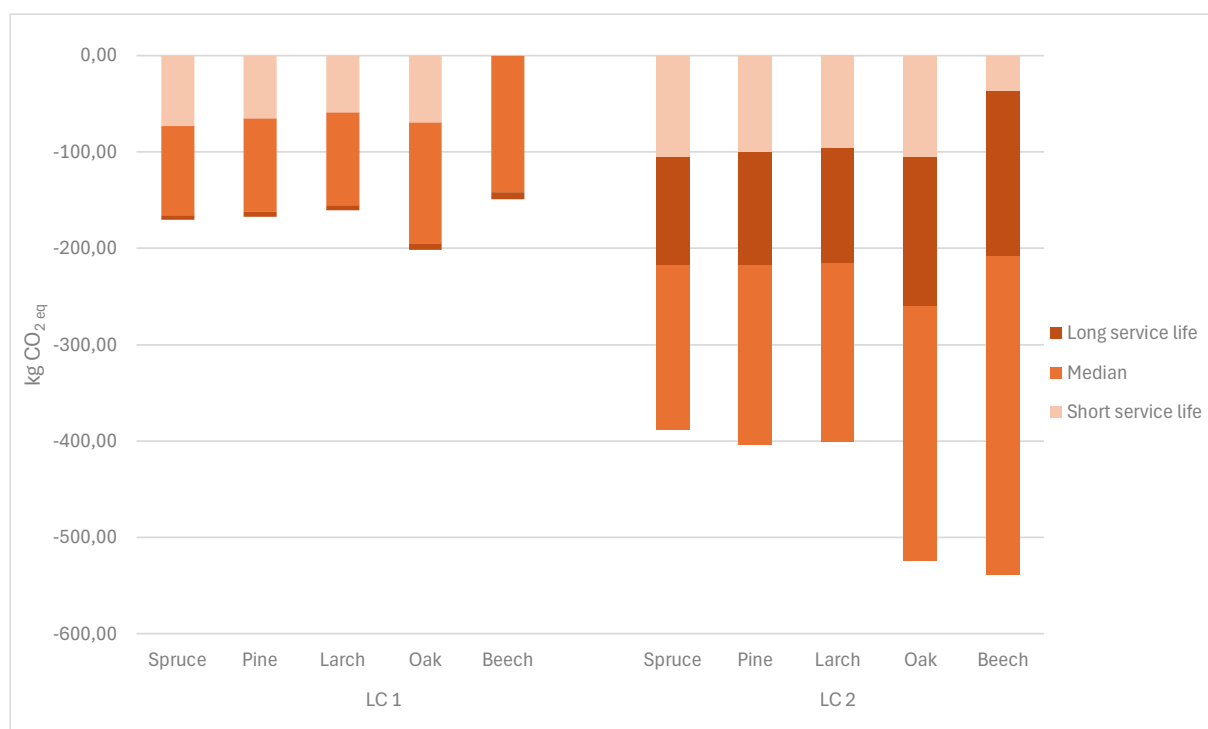


Figure 5. Impact of service life variation for allocation method R3

