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André Manuel Alves Dias

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A CRADLE-TO-GRAVE PERSPECTIVE

Tese no âmbito do Doutoramento em Engenharia Civil, Estruturas orientada pelo Professor Doutor Alfredo Manuel Pereira Geraldes Dias, Professor Doutor José Dinis Silvestre e Professor Doutor Jorge Manuel Caliço Lopes de Brito e apresentada ao Departamento de Engenharia Civil da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

Dezembro de 2021

Faculdade de Ciências e Tecnologia da Universidade de Coimbra

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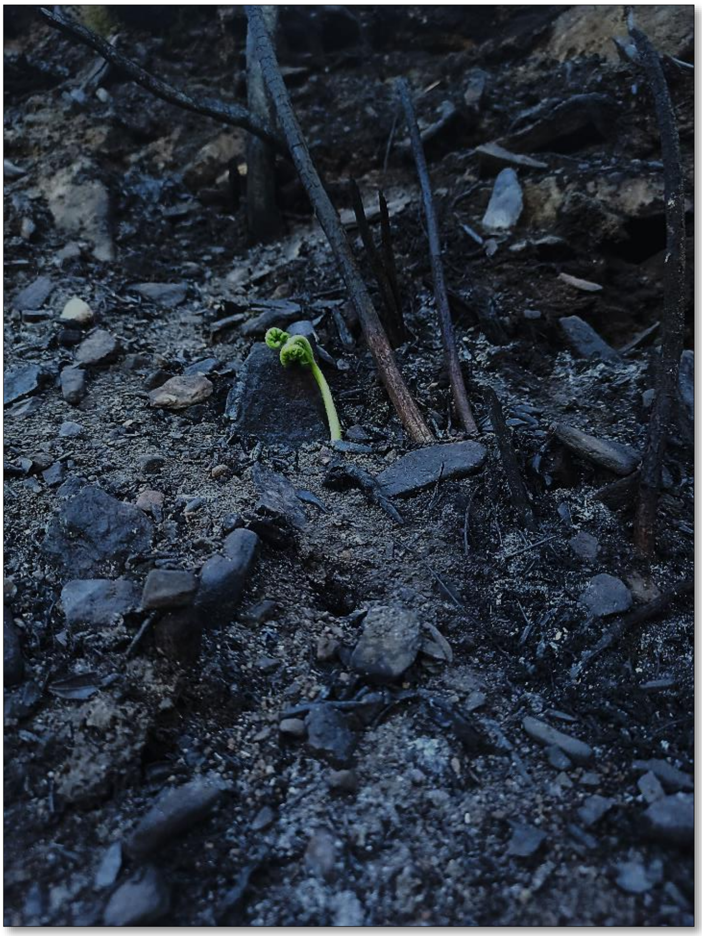

In memoriam,
Diogo Miguel Alves Dias
(15/09/1998 – 25/07/2020)

“Se a morte que espreita escondida
Me desse o destino a escolher
Perdia o folgo e partia
P’ra um dia te voltar a ver

Sorrisos e abraços perdidos
Olhares suspensos no ar
Palavras que ficam gravadas
Procuro te quero encontrar

E enquanto caminho sozinho
O vento que sopra zangado
Ele diz que a vida é ingrata
Que um dia estarei a teu lado”

João Moreno / Grupo de Fado Amanhecer

AGRADECIMENTOS

Este projeto começou a fazer sentido para mim ainda antes de começar a frequentar as disciplinas do curso de Doutoramento em Engenharia Civil na Universidade de Coimbra. A principal motivação foi a minha paixão por Engenharia Civil, pela floresta portuguesa, pelos produtos de madeira e pela busca de conhecimento. Quis o fado que durante a realização deste projeto tivesse a sorte de trabalhar com pessoas que alimentaram esta minha paixão e contribuíram, com o seu profissionalismo e entrega, para a realização deste documento. Sem eles não teria sido possível.

O exercício de transformar sentimentos de gratidão é sempre difícil: para quem o faz, por receio de não transmitir o sentimento na intensidade que pretende; e para quem o lê, por muitas das vezes achar redutor o conteúdo das palavras. Aos que agradeço de seguida, sintam cada palavra com a mesma intensidade com que colaboraram para a realização deste trabalho.

Primeiramente gostaria de agradecer à Fundação para a Ciência e Tecnologia (FCT), enquanto entidade financiadora da bolsa de Doutoramento que me foi atribuída (PD/BD/135159/2017) através do programa doutoral em Eco Construção e Reabilitação (EcoCoRe). O programa Doutoral EcoCoRe garantiu o subsídio de bolsa, o pagamento das propinas e um subsídio complementar de apoio à realização dos trabalhos, apoios esses que se tornaram essenciais para a realização deste trabalho.

Um agradecimento especial à Universidade de Coimbra (UC) e, em particular, ao Departamento de Engenharia Civil (DEC), por me terem proporcionado todas as condições necessárias à realização do presente trabalho. Gostaria de agradecer igualmente ao Institute for Sustainability and Innovation in Structural Engineering (ISISE), como unidade de investigação, que proporcionou todas as condições essenciais ao desenvolvimento do trabalho.

Um agradecimento especial à direção do SerQ - Centro de Inovação e Competências da Floresta (Doutor Paulo Luís, Doutor José Saporiti e Doutor Alfredo Dias) por me terem proporcionado todas as condições para a realização deste trabalho, em especial pela disponibilização de espaços e aquisição de software.

Um agradecimento especial aos meus orientadores. Sem eles não teria sido possível realizar este trabalho. Os seus conhecimentos foram essenciais para conseguir ultrapassar as dificuldades que surgiram. Foram também essenciais para motivar a minha superação pessoal e a aprofundar conhecimentos em áreas que eram para mim desconhecidas e onde não me sentia à vontade. De forma particular: ao Professor Alfredo Dias, por sempre ter acreditado nas minhas capacidades, por se ter disponibilizado para resolver todos os problemas que surgiram, e pela motivação constante ao longo dos trabalhos; ao Professor José Silvestre, pelo esforço e dedicação no acompanhamento e revisão dos trabalhos e pela persistência e paciência na transmissão dos seus conhecimentos; ao Professor Jorge de Brito, por ter incutido um espírito de superação e desenvolvimento profissional e por, através da sua exigência, ter contribuído para a qualidade académica dos trabalhos realizados. Não posso deixar de destacar o humanismo e espírito construtivo dos meus orientadores que foram essenciais para gerar um bom ambiente de trabalho. Sinto que para além de terem contribuído para o meu desenvolvimento profissional, contribuíram também para o meu desenvolvimento pessoal.

Um agradecimento especial à Engª Ana Fernandes da empresa PinhoSer (Grupo Palser): por ter colaborado desde o início com este trabalho, por ter disponibilizado todos os dados por mim solicitados para a realização deste trabalho, e por acreditar que a ligação entre a investigação e a indústria é possível e benéfica para ambos os lados.

Um agradecimento especial ao Dr. Manuel Martins da empresa Abastena: por se ter disponibilizado para colaborar com este trabalho, e por ter disponibilizado os dados relativos à produção de Pinheiro-Bravo e Eucalipto para a realização deste trabalho. Agradeço de igual forma ao Eng.º Vasco Medeiros, Diretor dos Serviços Florestais da Secretaria Regional da Agricultura e Florestas do Governo dos Açores pela disponibilização de dados relativos à produção de Criptoméria no Açores, o que tornou possível incluir esta espécie neste trabalho.

Um agradecimento especial ao Mário Dias, ao Sr. António Cardoso e à Sra. Fátima Ribeiro da empresa Madeiras Fátima António & Filhos Lda. pela forma como desde o início colaboraram com este trabalho, pela forma construtiva como transmitiram os seus conhecimentos e pela disponibilização de dados.

Agradeço ao Eng.º Nelson Pedrosa da empresa Pedrosa e Irmãos, Lda., por ter acreditado neste projeto e ter colaborado sempre que por mim solicitado. Agradeço também ao Eng.º Artur Feio por ter colaborado com este projeto. Igualmente ao Eng.º André Nunes por ter ajudado a perceber algumas dúvidas relacionadas com a gestão florestal. De igual forma agradeço ao Eng.º Ricardo Reis da empresa InWood por ter aceitado colaborar com o seu conhecimento para este trabalho.

À Professora Helena Gervásio, Professora Sandra Monteiro, e Professor Luís Jorge pelos preciosos comentários construtivos feitos aquando da defesa do projeto tese. Ao Professor Luís Jorge agradeço também a sua disponibilidade em esclarecer dúvidas relacionadas com o sector da construção em madeira.

Aos colegas do SerQ pelo bom ambiente de trabalho que disponibilizaram durante a realização deste trabalho, em especial aos colegas André Marques, Pedro Gil, Sofia Knapic, Ângela Neves e José Pereira por me terem ajudado a esclarecer dúvidas relacionadas com este trabalho. Agradeço também aos colegas que conheci durante os últimos 4 anos e que colaboraram com este trabalho, em especial aos colegas: Vera Durão, Eduardo Oliveira, e Samuel Esteves.

A todos os Professores que conheci e de quem tive a sorte de ser aluno durante o meu percurso académico, por, mesmo sem saberem, estavam a deixar em mim o gosto pelo conhecimento e a curiosidade pela ciência.

À Sofia Dias, a de sempre, pela forma incansável como me manteve motivado durante este trabalho, pelo modo como soube lidar com os altos e baixos deste trabalho, e por ser um pilar na minha vida.

Aos amigos Pedro Carrilho e João Lobo por sempre se disponibilizarem a colaborar com este trabalho quando assim necessitei. Aos colegas da *Tertúlia Académica PPdeCE*, Alexandre Mota, Hélder Fernandes, Diogo Sabino, Pedro Graça, Manuel Ribeiro, Daniel Paiva e José Lourenço; e aos amigos da *Turma B*, Pedro Ribeiro, Rodrigo Gonçalves, Daniel Ramos, Valentina Cristóvão, Ana Cardoso e Mónica Lopes pela motivação que sempre me deram durante o meu percurso académico, especialmente durante os momentos mais difíceis dos últimos anos.

À Anabela Ramos e ao Tiago Pires pela pronta disponibilização a apoiar-me a receber-me em sua casa durante o período em que frequentei o curso de ACV no IST, em Lisboa.

A toda a minha família e em especial aos meus pais pelo exemplo que sempre foram para mim, por me terem apoiado sempre nas minhas decisões, por me terem sempre motivado a superar a mim próprio e pela educação e valores que me transmitiram. Aquilo que sou deve-se principalmente a eles.

Por último, e o mais importante, ao meu irmão Diogo: pelo exemplo de entrega que deixou, pela forma apaixonada com que viveu e assim me motivar também a continuar a viver. A ele, dedico este trabalho. Até um dia.

RESUMO

O aumento das preocupações com o meio ambiente tem levado a um aumento, em todo o Mundo, de iniciativas que promovem a redução dos impactes ambientais dos produtos e serviços utilizados pela Sociedade. Na Europa, o setor da construção é responsável por aproximadamente 40% do consumo total de energia e 36% das emissões de dióxido de carbono para a atmosfera. Desta forma, é importante que as decisões a serem tomadas neste setor tenham também em consideração os impactes ambientais dos produtos e serviços. A Avaliação do Ciclo de Vida (ACV) é uma metodologia regulada por normas Globais e Europeias, que tem como objetivo a quantificação de impactes ambientais de produtos e serviços. Esta metodologia foi utilizada em outros estudos para quantificar e comparar os impactes ambientais de vários produtos e várias soluções construtivas. Alguns desses estudos identificaram benefícios ambientais em utilizar produtos à base de madeira na construção, principalmente devido ao dióxido de carbono capturado durante a fase de crescimento das árvores.

Neste contexto, este estudo aplicou a metodologia de ACV à realidade portuguesa da construção com produtos à base-de-madeira, tendo como objetivos: i) identificar os procedimentos que devem ser seguidos para quantificar os impactes ambientais de produtos e soluções à base de madeira, ii) identificar os procedimentos de dimensionamento estrutural e de dimensionamento para a durabilidade que devem ser seguidos no dimensionamento de estruturas de base-de-madeira, iii) definir métodos de comparação de produtos e soluções tendo por base o seu comportamento estrutural, iv) comparar os impactes ambientais de madeira em toro variando espécies de madeira, país de origem e modelos de gestão florestal, v) comparar os impactes ambientais de diferentes produtos e soluções estruturais para um pavimento residencial, vi) comparar os impactes ambientais de diferentes soluções de durabilidade para um deck exterior, vii) identificar “hotspots” ambientais do ciclo de vida de produtos estruturais à base de madeira, e viii) analisar a influência de diferentes abordagens de ACV nos impactes ambientais das diferentes soluções.

Neste estudo, a quantificação de impactes ambientais de produtos à base de madeira através da metodologia de ACV foi feita seguindo os procedimentos recomendados pelas normas Globais e Europeias (ISO 14040, ISO 14044, EN 15804 e EN 16485). O dimensionamento estrutural e de durabilidade de produtos de madeira seguiu as regras dadas pelas normas: EN 1990, EN 1991, EN 1995 e EN 350. Os métodos desenvolvidos para a comparação de produtos estruturais tiveram por base os métodos de determinação das classes de resistência definidos pela EN 14081-1 (visual e mecânico) e as propriedades de resistência à flexão e módulo de elasticidade dos produtos. Os métodos de comparação de soluções estruturais e de durabilidade seguiram as normas de dimensionamento europeias.

A comparação da madeira em toro analisou os impactes ambientais de: Pinheiro-bravo (*Pinus Pinaster*), Criptoméria (*Cryptomeria Japonica*), Eucalipto (*Eucalyptus globulus*), Pinho Silvestre (*Pinus Sylvestris*), e Espruce (*Picea Abies*); com origem em Portugal, Suécia e Alemanha; e com diferentes modelos de gestão florestal. A Criptoméria foi a espécie que apresentou menor impacte ambiental na maioria das categorias ambientais. O Eucalipto foi a espécie que apresentou os maiores impactes ambientais. Os modelos de gestão da Alemanha apresentaram maior impacte ambiental do que os Suecos. Para o Pinheiro-bravo, o modelo de gestão que considera a regeneração natural das árvores foi o que apresentou menor impacte ambiental.

Para o pavimento residencial, foram comparadas soluções de diferentes tipos de produtos: madeira serrada (mesmas espécies do que madeira em toro) (SW), madeira lamelada colada (GLT), madeira microlamelada (LVL) e vigas mistas em forma de I com OSB na alma e SW e LVL nos banzos (I-Joists). Para a totalidade do ciclo de vida, as soluções de produtos com LVL (LVL e I-Joists) tiveram maior impacte ambiental na maioria das categorias. Por outro lado, o SW de Pinheiro-bravo apresentou os menores impactes ambientais.

Nas soluções para o uso de madeira num deck exterior, variaram: as espécies de madeira (as mesmas do que na madeira em toro), método de tratamento (superficial e em profundidade) e os produtos aplicados. A Criptoméria tratada com tratamento superficial teve o menor impacte na maioria das categorias de impacte. Por outro lado, Pinheiro-bravo tratado com tratamento superficial teve o maior impacte ambiental na maioria das categorias.

A análise dos impactes ambientais durante o ciclo de vida identificou que, durante a fase de gestão florestal, as operações que tiveram maior influência na maioria das categorias ambientais foram a fertilização e o desbaste feito com motosserras. Durante a fase de produção de madeira serrada, a principal influência dos impactes deveu-se ao consumo de energia e gasóleo. Para os produtos usados no deck exterior, o fabrico de produtos preservadores teve a maior influência na maioria das categorias de impacte.

Por fim, a análise da influência de procedimentos de ACV nos resultados identificou que uma alocação volúmica levou a um menor impacte ambiental de madeira em toro e de madeira serrada. As principais diferenças da escolha de diferentes bases de dados de inventário estão relacionadas com as modelações de produção e consumo de combustíveis.

Palavras-Chave: Avaliação do Ciclo de Vida, Estruturas de madeira, Madeira serrada, Madeira Lamelada Colada, Madeira Microlamelada, Vigas em I.

ABSTRACT

The increasing concern for the environment has led to a worldwide increase of initiatives that promote the reduction of the environmental impacts of products and services used by Society. In Europe, the construction sector is responsible for approximately 40% of total energy consumption and 36% of carbon dioxide emissions into the atmosphere. It is therefore important that decision-making in this sector takes into account the environmental impacts of products and services. Life Cycle Assessment (LCA) is a methodology regulated by Global and European standards that intends to quantify the environmental impacts of products and services. It has been used in scientific and industrial studies to quantify and compare the environmental impacts of various products and construction solutions. Some of these studies have identified environmental benefits from the use of wood-based products in construction, mainly due to the carbon dioxide captured during the growth phase of the trees.

In this context, this study intends to apply the LCA methodology to the Portuguese reality of construction with wood-based products, through the following objectives: i) identification of the LCA procedures that must be followed to perform a LCA study of wood-based structural and durability solutions, ii) identification of the structural and durability design procedures of wood-based structures, iii) definition of the methods for comparison of products and solutions based on structural and durability equivalence units, iv) comparison of the environmental impacts of roundwood of various wood species, countries of origin and forest management, v) comparison of the environmental impacts of various structural products and solutions for a residential floor, vi) comparison of the environmental impacts of various durability solutions for a deck floor, vii) identification of the environmental hotspots during the life cycle of wood-based structural and durability solutions, and viii) analysis of the influence of variations of LCA approaches on environmental impacts of various solutions.

In this study, the quantification of environmental impacts of wood-based products through LCA methodology was performed following the procedures recommended by the Global and European standards (mainly ISO 14040, ISO 14044, EN 15804, and EN 16485). The structural and durability design of wood products followed the rules given by the standards EN 1990, EN 1991, EN 1995 and EN 350. The methods developed for the comparison of structural products were based on the methods for determining the strength classes defined by EN 14081-1 (visual and mechanical) and bending strength and modulus of elasticity. The methods for comparison of structural and durability solutions followed the European design standards.

The comparison of roundwood analysed the environmental impacts of: Maritime pine (*Pinus Pinaster*), Cryptomeria (*Cryptomeria Japonica*), Eucalyptus (*Eucalyptus globulus*), Scots pine (*Pinus Sylvestris*), and Norway spruce (*Picea Abies*); from Portugal, Sweden and Germany; and with different forest management models. Cryptomeria was the wood species that showed the lowest environmental impact on the majority of the environmental categories. Eucalyptus was the wood species that presented the highest environmental impacts. German management models showed higher environmental impacts than Swedish models. As regards the Maritime pine, the forest management model that considers natural regeneration of the trees had the lowest environmental impacts.

For a residential floor, the following four products were compared: sawnwood (same species as roundwood) (SW), glued laminated timber (GLT), laminated veneer lumber (LVL) and I-beams with OSB on the core and SW and LVL on the flanges (I-Joists). For the whole life cycle, the solutions that used LVL (LVL and I-Joists (OSB + LVL)) had the highest impacts in most environmental categories. On the other hand, SW of Maritime pine had the lowest environmental impacts.

In the solutions for the use of wood in a deck varied the: wood species (same as roundwood), treatment method (surface and pressurised) and products applied. Cryptomeria treated with surface treatment had the lowest impacts in most environmental categories. On the other hand, surface treated Maritime pine had the highest impacts in most environmental categories.

The analysis of the environmental impacts during the life cycle identified that, during the forest management phase, the operations with the greatest influence on the majority of environmental categories were fertilisation and thinning carried out with chainsaws. During the sawnwood production phase, the main influence of impacts was due to energy and diesel consumption. For the products used in the deck, the production of preservatives had the highest influence in most impact categories.

Finally, the analysis of the influence of LCA procedures on the results identified that the volumetric allocation led to a lower environmental impact of roundwood and sawnwood. The choice of different databases for inventory influences mainly the impacts related to fuel production and consumption.

Keywords: Life Cycle Assessment, Timber structures, Sawnwood, Glued laminated Timber, Laminated Veneer Lumber, I-Joists beams

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SYMBOLOGY

def_m	Deformation in the middle span
def_{max}	Maximum deformation in the middle span
$E_{0,mean}$	Mean modulus of elasticity parallel to the fibres
$E_{90,mean}$	Mean modulus of elasticity perpendicular to the fibres
$f_{c,0,k}$	Characteristic compressive strength parallel to the fibres
$f_{c,90,k}$	Characteristic compressive strength perpendicular to the fibres
$f_{m,k}$	Characteristic bending strength
$f_{r,k}$	Characteristic shear plane strength
$f_{t,0,k}$	Characteristic tensile strength parallel to the fibres
$f_{t,90,k}$	Characteristic tensile strength perpendicular to the fibres
$f_{v,k}$	Characteristic shear strength
$G_{mean,per}$	Mean shear modulus perpendicular to the fibres
$G_{mean,r}$	Mean shear modulus parallel to the fibres
h	Height of beam cross section
I	Moment of inertia
k_{mod}	Modification factor for duration of load and moisture content
k_{sys}	System strength factor
$k_{c,90}$	Increase factor of the compressive strength perpendicular to the grain
k_{cr}	Crack factor
k_{crit}	Reduction factor for strength due to the effects of lateral buckling
k_{def}	Deformation factor
kh	Depth factor
k_m	Modification factor that considers the redistribution of bending stresses in a cross-section
k_{sys}	Increase factor for structural strength
k_v	Reduction factor for notched beams
k_{vol}	Volume factor
l	Length of beam

M	Bending moment
P	Distributed load
σ_m	Design bending stress
w	Width of beam cross section
γ_M	Partial factor for product properties
ρ_k	Characteristic density
ρ_{mean}	Mean density

ABBREVIATIONS

ACQ	Alkaline Copper Quaternary
ADPE	Mineral and Fossil Resource Depletion
ADP-f	Resource Use Potential, Fossils
ADPM	Non-Fossil Resource Depletion
ADP-m	Resource Use Potential, Minerals and Metals
AP	Acidification Potential
CEN	European Committee for Standardization
CLT	Cross Laminated Timber
CN	Water-Borne Copper Naphthenate
CNo	Oil-Borne Copper Naphthenate
Cryt_Plant_PT	Cryptomeria Planted
DDAC	Copper And Didecyldimethylammonium Chloride
EC	Eurocode
ECHA	European Chemicals Agency
EDB	Data From Ecoinvent Database
EPD	Environmental Product Declarations
EP-f	Eutrophication Potential, Freshwater
EPI	Emulsion Polymeric Isocyanate Resin
EP-m	Eutrophication Potential, Marine
EP-t	Eutrophication Potential, Terrestrial
ETP-fw	Ecotoxicity Potential, Freshwater
Euc_Plant_PT	Eucalyptus Planted
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse gases
GLT	Glued Laminated Timber
GWP-b	Global Warming Potential - Biogenic
GWP-f	Global Warming Potential - Fossil
GWP-luluc	Global Warming Potential - Land use and LU change

GWP-t	Global Warming Potential - total
HTP-c	Human toxicity Potential, non-cancer
HTP-nc	Human toxicity Potential, cancer
IJ	I-Joist
IJ_C24	I-Joist with C24 wood in flanges
IJ_LVL	I-Joist with LVL in flanges
IRP	Ionising radiation Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LVL	Laminated Veneer Lumber
MC	Moisture content
MCQ	micronized copper quaternary
MF	Melamine-Formaldehyde
MP_C18	Maritime pine sawnwood classified as C18
MP_C24	Maritime pine sawnwood classified as C24
MP_C35	Maritime pine sawnwood classified as C35
MP_NR_PT	Maritime pine natural regeneration
MP_Plant_PT	Maritime pine planted
MP_rejected	Maritime pine sawnwood classified as rejected
MP_Seed_PT	Maritime pine seeded
MUF	Melamine-Urea-Formaldehyde
NDB	Data from national databases
ODP	Ozone depletion Potential
OSB	Orientated Strand Board
PCR	Product Category Rules
PEF	Product Environmental Footprint
PF	Phenol-Formaldehyde
PM	Particulate matter
POCP	Photochemical Ozone Formation Potential
PRF	Phenol-Resorcinol-Formaldehyde
PT	Pressurised treatment

PUR	Polyurethane resin
ReVa	Reference Values
RF	Resorcinol-Formaldehyde
RSL	Reference Service Life
SC	Service Classes
SLS	Service Limit States
SPine_Plant_DE	German Scots pine planted
SPine_Plant_SE	Swedish Scots pine planted
SPrc_Plant_DE	German Spruce planted
Sprc_Plant_SE	Swedish Spruce planted
SQP	Land use Potential
ST	Surface treatment
SW	Sawnwood
SW_Cryp_PT	Cryptomeria sawnwood produced in Portugal
SW_Euc_PT	Eucalyptus sawnwood produced in Portugal
SW_MP_PT	Maritime pine sawnwood produced in Portugal
SW_SPine_DE	Scots pine sawnwood produced in Germany
SW_SPine_SE	Scots pine sawnwood produced in Sweden
SW_SPrc_DE	Spruce sawnwood produced in Germany
SW_SPrc_SE	Spruce sawnwood produced in Sweden
UC	Use Class
UF	Urea-Formaldehyde
UK	United Kingdom
ULS	Ultimate Limit States
VOC	Volatile organic compounds
WDP	Water use Potential
ZN	water-borne zinc naphthenate

1 INTRODUCTION

1.1 Context and motivation

The 1987 report of the Bruntland commission, "*Our Common Future*", defines sustainable development as the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987). In September 2015, some countries, under proposal of the United Nations, adopted 17 goals for a sustainable development to accomplish until 2030, with the aims of: ending poverty, protecting the planet and ensuring prosperity for all (UN General Assembly, 2015).

Recently, the European Commission proposed to cut at least 40% of greenhouse gas emissions (from 1990 levels), to reach a share of at least 32% of renewable energy and to improve at least 32.5% the energy efficiency before 2030, and to be climate neutral before 2050. To achieve these goals, the European Commission launched the European Green Deal (European Commission, 2019b), which includes an action plan to boost the efficient use of resources by moving to a clean circular economy, which can contribute to restore biodiversity and reduce pollution. This action plan includes investment in environmentally friendly technologies, the decarbonisation of the energy sector and an increase in the share of energy efficient buildings.

The building sector is responsible for approximately 40% of the energy consumption (and the largest consumer) and 36% of the CO_2 emissions in the European Union (European Commission, 2019a). The building sector will thus face the challenge of reducing the energy consumption and the greenhouse gas emissions in the next years. In order to reduce the building construction's environmental impacts, the environmental burdens of the construction products and/or solutions shall be compared during the design stage to provide the decision-makers with more sustainable choices.

With the increasing consequences and concerns over climate change already highlighted, it is important that decisions that put our future at risk are based on methodologies that have already been scientifically and technically validated. Life Cycle Assessment (LCA) is a methodology proposed by ISO 14040 (ISO, 2006b) and ISO 14044 (ISO, 2006c) that "compiles and evaluates the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". This methodology is currently used to quantify the environmental impacts associated with a product or a system. Social and economic impacts are typically outside the scope of LCA. Nevertheless, they can also be addressed through other methodologies in combination with LCA.

LCA methodology has been used by academia and industry to quantify and compare the environmental impacts of products and solutions used in the construction sector (Dodoo *et al.*, 2014; Pajchrowski *et al.*, 2014; Peñaloza *et al.*, 2016; Robertson *et al.*, 2012; Skullestad *et al.*, 2016). In these studies, wood-based products have been highlighted due to their environmental characteristics. One of the main advantages of using wood-based products is related to the trees' ability to "capture" carbon dioxide that exists in the atmosphere and retain the carbon in the wood products.

Besides the reduced impact on Global Warming, wood-based products also show advantages in the reduction of environmental impacts due to their possibility of being used at their end-of-life, for example for energy production (Thonemann & Schumann, 2018). Although the advantages of wood products are identified, it is important to quantify these advantages and compare them with other products on the market in order to make sustainable decisions supported by scientific knowledge.

In recent years, due to the development of new technologies and products which make it possible to exceed some of the limitations of wood-based products, their use in the construction sector has increased. This dynamic shall be complemented with the development of methods based on Global and European rules and standards to calculate and compare the environmental impact of wood products.

The calculation of environmental impacts through the LCA methodology allows the identification of the operations in the life cycle of wood products that most influence the results (environmental "hotspots"). Aiming at the environmental optimisation of wood-based building solutions, after the identification of hotspots, it is important to study which changes should be made in the life cycle operations that lead to a reduction of their environmental impacts.

Thus, this study proposes an environmental optimisation of wood-based construction solutions by developing comparison methods and applying them to different alternatives during the life cycle of the solutions. Such comparison allows companies in the wood-based construction sector (from tree planting to incineration and/or landfilling of products) to make decisions that reduce the environmental impacts and ensure a sustainable development.

This study compares the environmental impacts of various alternatives for:

i) Wood species of sawnwood,

ii) Country of origin of sawnwood,
iii) Forest management scenarios,
iv) Structural wood-based products,
v) Strength classes of sawnwood, glued laminated timber, and I-joists,
vi) Structural configuration of building solutions,
vii) Preservative treatment methodologies,
viii) Preservative products,
ix) Durability plans,
x) End-of-life scenarios for wood products.

1.2 Objectives and methodology of the study

The main objective of this PhD thesis is the LCA of wood-based solutions. The structural and durability performances of these solutions are analysed separately and are referred to hereafter as "structural solutions" and "durability solutions". In order to achieve this main objective, a number of intermediate objectives must be attained, and these are described below.

- Identify the LCA procedures that must be followed to perform a LCA study of wood-based structural and durability solutions.

This objective intends to identify the LCA procedures and processes that a LCA study must consider. To achieve this objective, a literature review of LCA standards (ISO 14040 (ISO, 2006b), ISO 14044 (ISO, 2006c), EN 15804+A2 (CEN, 2019)) and studies that assessed the LCA of wood-based products is performed. The information collected within the accomplishment of this objective is useful to support the goal, scope and inventory decisions made during this study.

- Identify the structural and durability design procedures of wood-based structures.

This objective is to identify the procedures and rules given by European standards for the structural and durability design of wood-based structures. This objective is achieved by reviewing the design procedures given by European standards for structural (EN 1995-1-1 (CEN, 2014c)) and durability (EN 335 (CEN, 2013b) and EN 350 (CEN, 2016b)) designs. The information collected is used to perform structural and durability designs of various case studies and define the equivalent functional units.

- Define methods for comparison of products and solutions based on structural and durability equivalence units.

This objective is to propose and compare various methodologies that take into account the structural and durability design variables of various wood products. These methodologies propose assessments at the product level (based on i) visual and mechanical grading methodologies, and ii) bending strength and mean modulus of elasticity properties of products) and at the building assembly level (based on a structural and on a durability equivalence). These methodologies will allow architects, engineers and LCA experts to identify the products, and the combinations of products, with better environmental performance.

- Compare the environmental impacts of roundwood from various wood species, countries of origin and forest management practices.

This objective intends to compare the environmental impacts of various wood species (Maritime pine (*Pinus Pinaster*), Cryptomeria (*Cryptomeria Japonica*), Eucalyptus (*Eucalyptus globulus*), Scots pine (*Pinus Sylvestris*), and Norway spruce (*Picea Abies*)) from various origins (Portugal, Germany and Sweden). The comparison of results will allow industries producing wood-based products (such as sawmills) to identify sustainable sources of roundwood and which forest management models (and operations) lead to products with better environmental performance.

- Compare the environmental impacts of various structural products and solutions for a residential floor.

This objective is to compare the environmental impacts of various structural products: Sawnwood (SW) (softwoods and hardwood), Glued Laminated Timber (GLT), Laminated Veneer Lumber (LVL) and I-Joist beams (IJ). The comparison of results will allow different actors of the construction sector (such as engineers and architects) to identify sustainable wood-based products and solutions.

- Compare the environmental impacts of various durability solutions for a deck floor.

This objective is to compare the environmental impacts of various sawnwood species (Maritime pine (*Pinus Pinaster*), Cryptomeria (*Cryptomeria Japonica*), Eucalyptus (*Eucalyptus globulus*), Scots pine (*Pinus Sylvestris*), and Norway spruce (*Picea Abies*)) treated by different preservation methods and products (penetrating vacuum-pressure and surface brushing). The comparison of results will allow different actors of the construction sector (such as engineers and architects) to identify sustainable durability combinations of wood species and preservative products.

- Identify the environmental hotspots during the life cycle of wood-based structural and durability solutions.

This objective is to identify the operations performed during the life cycle of wood-based structural and durability solutions that had the highest influence on various environmental categories. The results will help the industries of the value chain of wood-based structures to reduce the environmental impacts of the life cycle of wood products.

- Analyse the influence of variations on LCA modelling procedures on the environmental impacts of various solutions.

This objective is to analyse the consequences of variations on LCA method procedures (such as allocation (volumetric, massic and economic) and LCI methodology (based on international and national databases)). The results will support LCA experts in making decisions for the modelling of LCA (goal and scope, life cycle inventory, life cycle impact assessment, and interpretation) of wood-based products.

1.3 **Document structure**

This document is composed of nine chapters:

- Chapter 1 - Introduction summarizes the aim of the thesis project, which includes the motivation of this study, the definition of goal and scope, as well as the methodology followed to achieve the goal and scope proposed. In the end, the structure of the document is presented.

- Chapter 2 – Life Cycle Assessment focused on the methodology of LCA defined by International Organization for Standardization (ISO) and European Committee for Standardization (CEN) series of standards. Starting with a framing of sustainable construction, this chapter analyses the phases of LCA (definition of goal and scope, life cycle inventory; life cycle impact assessment and interpretation). The types of environmental certifications of construction materials are also analysed. A literature review of the LCA of wood-based construction products (sawnwood, glued laminated timber, laminated veneer lumber, and I-joists beams) and of complementary products (adhesives and preservatives) is performed by analysing studies that assessed the environmental impacts through the life cycle of products and building solutions (production, construction, use and end-of-life). The Native LCA methodology (Silvestre *et al.*, 2015) is then applied to calculate the European Reference Values (ReVa) of wood-based products.

- Chapter 3 - Timber Structures presents and discusses the framework for the structural and durability design of timber structures. The structural design begins with an analysis of the microscopic and macroscopic structure of wood and of its inherent properties that influence its use in construction, namely the visual, physical, and mechanical properties. The visual and mechanical grading methodologies are presented. This section also describes the physical properties of the wood species and wood-based products studied in this document. The structural and durability design procedures given by European standards are also given in this chapter.

- Chapter 4 – Comparison of Structural Products and Solutions proposes six different methodologies for the assessment of the environmental impacts of structural products, structural solutions, and durability solutions. At the product level, two methodologies are proposed to allocate the environmental impacts to a specific strength class of sawnwood. For comparisons of sawnwood and other products, two methodologies are proposed based on the bending strength and on the mean modulus of elasticity of the products. Additionally, two methodologies that define equivalent functional units for comparison of structural and durability solutions are proposed.

- Chapter 5 – Definition of Case Studies gives the goal and scope of this study. This chapter defines the case studies, data collection methodologies, cut-off criteria, allocation procedures and data quality requirements. Functional units and system boundaries are also defined for each case study.

- Chapter 6 – Life Cycle Inventory describes the methodology followed for the collection of data for each case study. The data used to model the processes of each life cycle stage of the various case studies are also provided.

- Chapter 7 – Life Cycle Impact Assessment starts with a description of the impact assessment methodology used in this study and of each environmental category. The results of the environmental impacts of the various scenarios studied are presented and compared for each stage of assessment. In order to calculate and compare the magnitude of the environmental impacts of the various scenarios considered, the environmental impacts are normalised.

- Chapter 8 – Interpretation explains the environmental impacts of roundwood, structural products, structural floor solutions and deck solutions. For roundwood, calculation and comparison are made for the: i) environmental impacts from this study with literature results, ii) environmental impacts per life cycle operation, iii) environmental impacts of various scenarios using an economic allocation, and iv) environmental impacts of various scenarios using a different LCI modulation procedure. For structural products, this chapter calculates and compares: i) the environmental impacts of this study with ReVa calculated in Chapter 2, ii) the environmental impacts of various allocation procedures for the Maritime pine scenario, iii) the environmental impacts per life cycle operation, and iv) the environmental impacts for mechanical grading methodology and bending strength and modulus of elasticity methodologies proposed in Chapter 4. For structural floor solutions, this chapter calculates and compares: i) the volume of different design variables, and ii) the environmental impacts of modulation the incineration with energy recovery at the end of life. For deck solutions, this chapter calculates and compares: i) the environmental impacts per life cycle operation, and ii) the environmental impacts of different durability plans for Maritime pine solutions.

- Chapter 9 – Conclusions and Future Research presents the conclusions of the study, identifies its limitations and proposes future research themes.

2 LIFE CYCLE ASSESSMENT

2.1 Sustainable construction

The sustainable development can be divided into three different areas that must be tackled together: environmental, economic and social. In other words, a sustainable development must guarantee an economic efficiency, social inclusion, and environmental responsibility within the limits of the Planet.

In the European Union, it was estimated that in 2016 the construction sector represented about 9% of the gross domestic product (GDP) and provided 18 million direct jobs (European Commission, 2016). Notwithstanding the natural importance of the construction sector which provides the buildings and infrastructures needed, it also represents an important role in environmental, economic and social activities.

Beyond the functional and technical performance of buildings referred above, EN 15643-1 (CEN, 2010) proposes a system to assess the environmental, social and economic performance of buildings based on a life cycle approach. The main objectives of this standard are the determination of the impacts of buildings and the possibility of the decision-makers (e.g. client, designer) making choices that address their sustainability. For sustainable comparisons between different systems, the technical and functional requirements must be quantified. This quantification can be made through the definition of the "functional equivalent unit". Available European Standards to assess the sustainability of buildings are presented in Figure 1.

2.2 Life Cycle Assessment method

The life cycle assessment method is defined in ISO 14040 (ISO, 2006b) and ISO 14044 (ISO, 2006c) as a "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*". The first approach to the current method was developed by the Society of Environmental Toxicology and Chemistry (SETAC) in the last decade of the 20th century. The first public document related to LCA was published in 1993 by SETAC (Klöpffer, 2006) and became an important initial step for the International Organization for Standardization (ISO) Technical Committee to develop the first international standards on LCA.

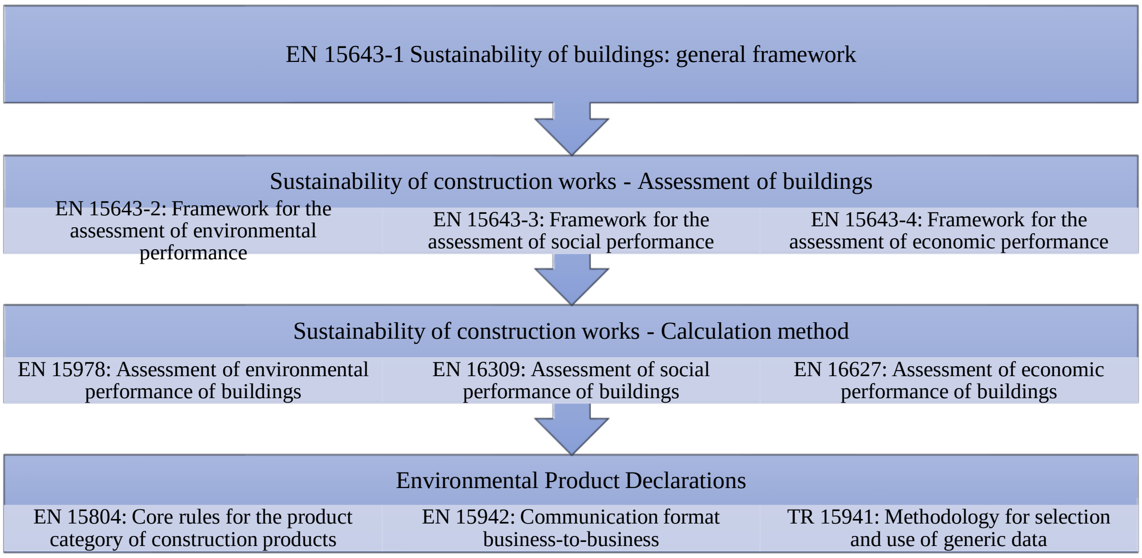

Figure 1 - European Standards to assess the sustainability of buildings

The first ISO publications related to LCA were:

- ISO 14040 - Principles and framework.
- ISO 14041 - Goal and scope.
- ISO 14042 - Life cycle impact assessment.
- ISO 14043 - Life cycle interpretation.

In 2006, the referred standards were replaced by ISO 14040 - Principles and framework (ISO, 2006b) and ISO 14044 - Requirements and guidelines. LCA is defined in ISO 14040 (ISO, 2006c) as an important tool to evaluate the environmental impacts throughout the product life cycle, from raw material acquisition to production, use, end-of-life treatment, recycling and final disposal.

A study of LCA is divided into four phases: goal and scope definition, inventory analysis, impact assessment and interpretation (Figure 2). One of the main advantages of the LCA methodology is the life cycle perspective of products, materials or production processes, which allows the identification and evaluation of the life cycle phases that most affect the environmental performance. It is thus possible to identify “environmental hotspots” in the life cycle of products and enable the increase of their environmental performance (Bouman *et al.*, 2000).

In the next sections, the standardized requirements for each of the LCA phases and their application in EPDs of wood and wood-based products based on EN 15804+A2 (CEN, 2019) and EN 16485 (CEN, 2014b) are presented.

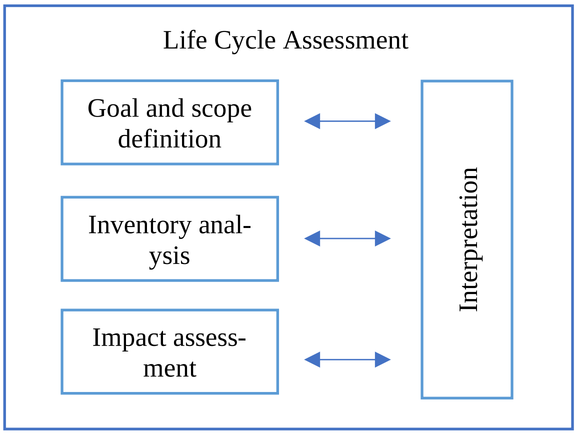

Figure 2 - Relation between LCA stages (adapted from ISO 14040)

2.2.1 Definition of goal and scope

A LCA study must describe the intention of realizing the study in the goal and scope definition stage. EN 14044 (ISO, 2006c) refers that the definition of the goal of a LCA study must answer the questions: “Application of study? Reasons for developing the study? Audience of the study? And if the results are intended to be disclosed to the public in comparative assertions”. The definition of scope must clarify:

- The product under study and its functions,
- The functional unit or declared unit,
- The system boundary,
- allocation procedures,
- cut-off criterion,
- data collection procedure,
- data quality requirements,
- Assumptions and limitations of the study.

Due to its complexity and influence on all the other issues, the functional unit and system boundaries of the study shall be clearly described.

2.2.1.1 **Functional unit, reference flow and functional equivalent unit**

A product or system may have many functions, so it is essential to define the functions considered in the study during the goal and scope phase. The definition of a functional unit must quantify the identified functions of the product. This entity must be meticulously described when the scope intends to compare different systems, to ensure that the basis for comparison is the same.

For each system, it is important to define the reference flow. It can be defined as the measure of the outputs from a product system used to relate the production outflow from the system and the functional unit.

When the goal and scope intend to compare functional and/or technical requirements of a building (or an assembled system) it shall be defined a functional equivalent unit (EN 15978 (CEN, 2011a)). The functional equivalence of a building (or an assembled system) shall include: the building type, relevant technical and functional requirements, pattern of use and required service life.

2.2.1.2 System boundary

The system boundary defines which unit processes are part of the product system and thus considered in the LCA study. The choice of processes to include within the system boundary shall be made based on a goal and scope definition, intended applications and audience, assumptions made, data and cost constraints, and cut-off criteria. All the assumptions made in the definition of the system boundary shall be identified and described, such as the cut-off criteria to exclude processes from the analysis.

The system boundary can be better understood if expressed in a flow diagram showing the unit processes and the flows of materials between them. For each unit process, the following must be described: the beginning of the process (where the process starts (reception of the raw materials), the operations performed as part of this process (intermediate process), and the end of the process (where the process ends (expedition of products)).

The LCA-based information for construction materials and buildings must cover the stages presented in Figure 3 (adapted from EN 15804+A2). In all stages, the provision and transport of materials, products, energy, and water use, as well as the processing of waste to the final state and its disposal, must be considered. When applicable, any types of losses during the processes should also be considered.

2.2.2 Life Cycle Inventory analysis (LCI)

The inventory phase consists of the collection of data, calculation and allocation procedures. The first step in LCI must be the definition of a plan for collecting and calculating data. ISO 14044 (ISO, 2006c) proposes the procedure shown in Figure 4 with the operational steps that should be performed to accomplish this phase.

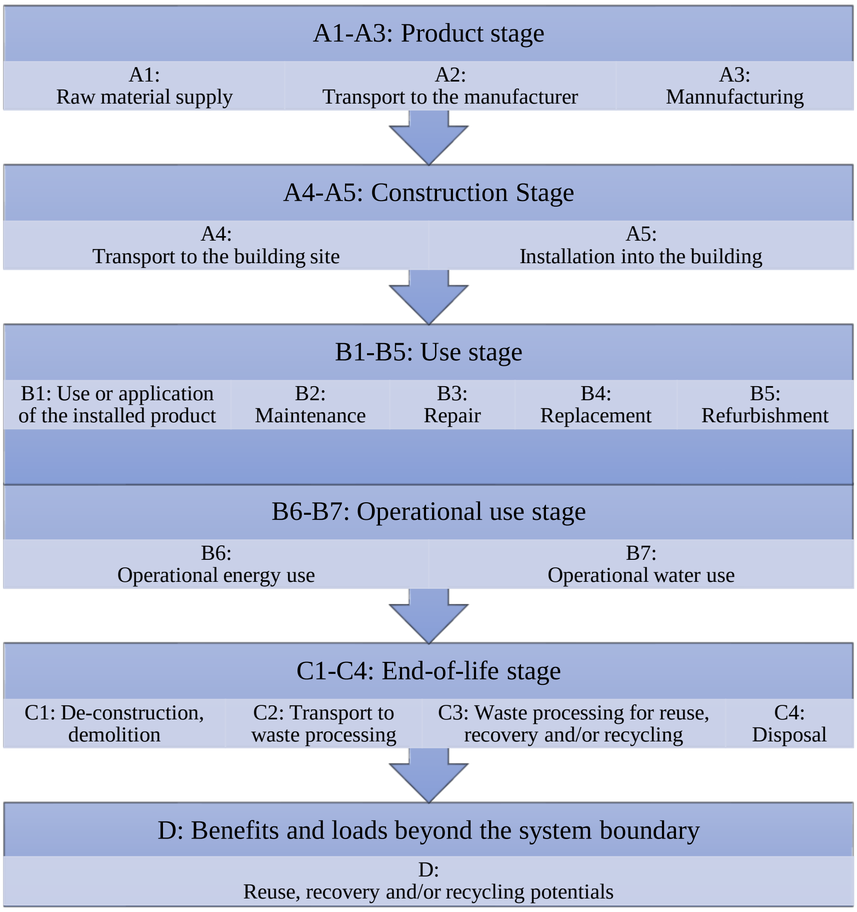

Figure 3 - Life cycle stages (adapted from EN 15804+A2)

As seen in Figure 4, an inventory analysis is an iterative process. During the data collection, new data requirements or limitations may arise, so the goal and scope of the study should be taken into account again. In some cases, this revision can lead to a goal and scope review and change.

2.2.2.1 **Data collection**

Data must be collected, measured, calculated, or estimated for each unit process and be used to quantify inputs and outputs of each unit process. For each unit process, collected data can be classified as: inputs (energy, raw materials, ancillary, and other physical inputs); outputs (products, co-products, and waste); emissions/discharges (to air, water and soil); or any other environmental aspects (ISO 14040 (ISO, 2006b)). Additionally, data representing noise and vibration, land use, radiation, odour, and waste heat must be collected.

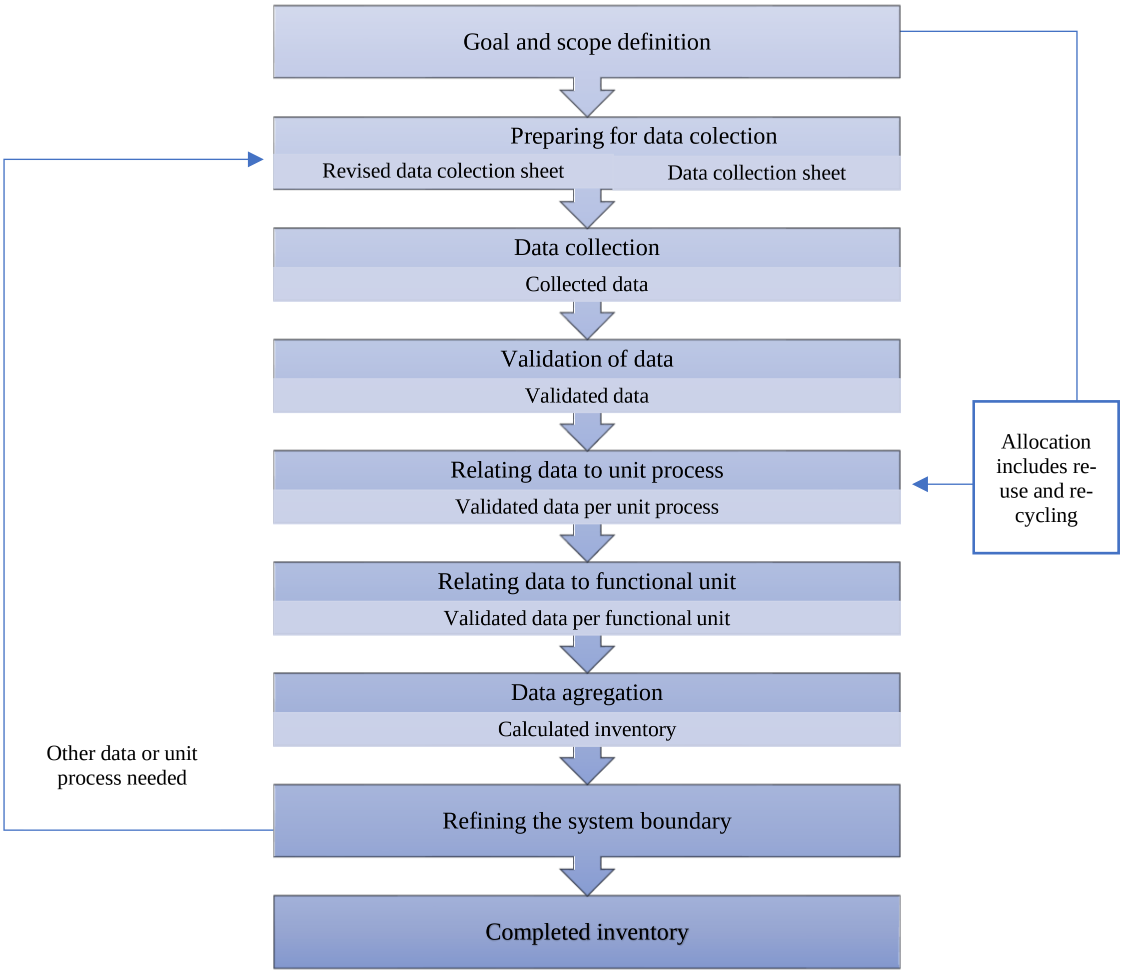

Figure 4 - LCI procedures (adapted from ISO 14044)

The data collected depend on the goal and scope of the study and must be collected from the production sites, respecting the system boundaries, associated, or collected and calculated from other sources. All data collected may include a mixture of measured, calculated, or estimated data.

Measurements should include flow diagrams of the unit processes and their flows to be modelled, a detailed description of each unit process and its influence on inputs and outputs, flows and relevant data for operation conditions associated to each unit process, list of units used, description of data collection and calculation techniques and instructions to clearly document any irregularity or special case.

The data quality requirements should address: time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, sources and uncertainty.

2.2.2.2 **Data calculation**

ISO 14044 (ISO, 2006c) refers that the data calculation procedures must be detailed, and the assumptions specified and explained. To be consistent, the same calculation procedures must be applied during the study. To determine the elementary flows associated with production, the current production mix of the company should be used in order to reflect the real mix production as much as possible.

During data collection, and in order to validate the data, a checklist to provide evidence and confirm the data quality requirements should be made. The validation of data can be performed by using mass balances, energy balances and/or comparative analyses of release factors. When anomalies are detected, data from other sources can be used, as referred in the previous section.

In practice, the data collected may not be in accordance with the functional unit, so it is necessary to define a reference flow. The collection of data related to the inputs and outputs of a unit process should be done for that reference flow and later converted in terms of functional unit.

If necessary, during the LCI, the system boundary can be revised, and a sensitivity analysis may be necessary to evaluate the significance of data. The cut-off criteria applied in a LCA study shall be clearly described and assessed. For inputs, the cut-off assessment can be based on mass, energy and environmental significance. A sensitivity analysis may result in the exclusion of life cycle stages or the unit process, and/or of inputs and outputs, both with lack of significance according to the goal and scope. A sensitivity analysis may also result in the inclusion of a new unit process or inputs/outputs that show to be significant for results.

2.2.2.3 **Allocation**

In the industry, it is usual that a process yields more than just one product; thus, to complete the LCI, it is necessary to resort to an allocation procedure (ISO 14044). Allocation is the partitioning of input and output flows of a complete process or of a product system between the product under study and other product systems. This way, the sum of inputs or outputs after allocation will be the same than before allocation. When identified, the necessity for allocation must follow the “allocation procedure” described below.

Allocation should be avoided, primarily by dividing the unit process to be allocated in more unit processes; or expanding system boundaries and including the sub-products and its information in the study. If allocation cannot be avoided, the inputs and outputs should be divided considering physical relations (e. g. mass or volume) between products and the boundaries of the unit process. When the physical relations between products are not enough to establish allocation, other relatable information should be used (e. g. economic).

In some outputs, it is possible that a part of it is considered a co-product and another a waste. In such cases, inputs and outputs must be allocated to the co-product part only. For the same system boundary and similar inputs and outputs, the allocation procedure must be uniformly applied.

For reuse and recycling, the allocation procedure described before must also be applied but demanding supplementary detail, for the following reasons: the inputs and outputs of the unit process considered can be shared by more than one product system; the reuse and recycling may change the properties of materials; and the recovery process for reuse and recycling needs specific care.

2.2.3 Life Cycle Impact Assessment (LCIA)

In the impact assessment phase, the main objective is the evaluation of the significance of the potential environmental impacts obtained using LCI data. In this phase, the inventory data is related to specific environmental impact categories. As for the LCI phase, this one requires an iterative process that can involve the reviewing or modifying of the goal and scope of the study. The start of a LCIA requires a verification of possible omissions or sources of uncertainty in other LCA phases, for example if data quality is enough to conduct the LCIA according to the goal and scope; if the system boundary and cut-off criteria are sufficiently reviewed to ensure the feasibility of LCI results; and if the environmental relevance of LCIA results is decreased by functional unit calculations, system wide averaging, aggregation and allocation. According to ISO 14044 (ISO, 2006c), the LCIA is composed by mandatory and optional elements and is shown schematically in Figure 5.

2.2.3.1 **Mandatory phases**

The first mandatory phase of LCIA is the selection of impact categories, category indicators and characterization models. Where existing models or new models are to be applied, the related information and sources shall be always referred. The selection of impact categories, category indicators and characterization models shall be justified and should be in harmony with the goal and scope. The impact categories selected shall reflect the environmental issues related to the product system under study and the defined goal and scope. The characterization model relates the LCI results and the category indicators providing a basis for characterization factors. In most cases of LCA studies, selection of impact categories, category indicators and characterization models are taken from existing models (Product Environmental Footprint (PEF)).

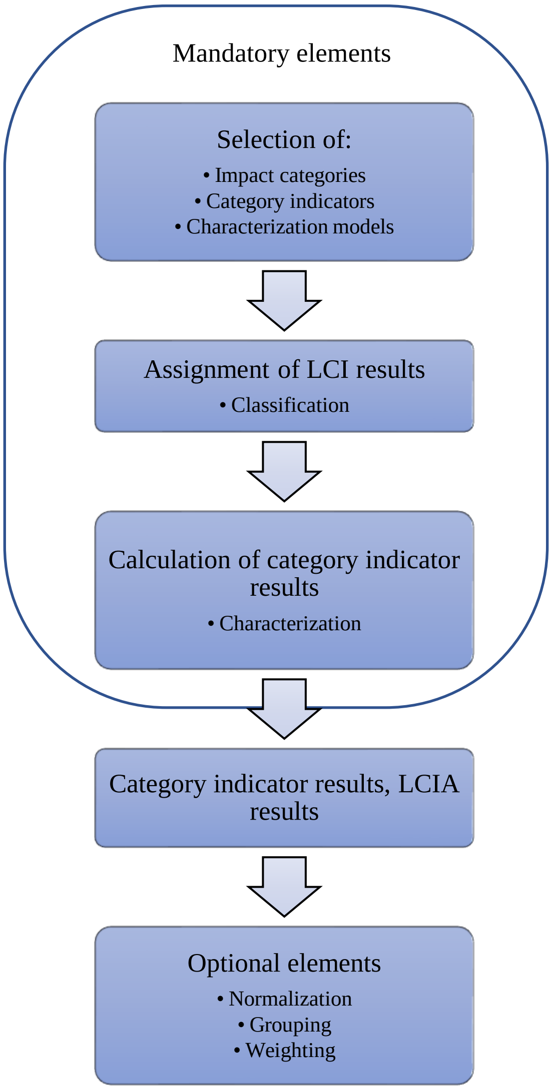

Figure 5 - LCIA phase description (adapted from ISO 14040)

For the second phase, unless otherwise stated in the goal and scope, the assignment of LCI results should consider: the assignment of LCI results exclusive to one impact category; identification of LCI results related to more than one impact category. The third phase, calculation of category indicator results, consists of the conversion of LCI results to common units and the sum of converted results within the same impact category. The output of this phase is a single numerical indicator result per impact category. The method, assumptions and value choices used in this process shall be identified and documented.

2.2.3.2 **Optional phases**

Depending on the goal and scope, more information based on LCIA mandatory results may be necessary. The optional phases proposed by standards are: normalization, grouping, weighting, and data quality analysis.

Normalization is the calculation of the magnitude of category impact results relative to reference data. Normalization is important in order to understand the relative magnitude of the impacts of the product system under study and can be helpful to: search for inconsistencies, allocate relative significance to the results obtained, and prepare for additional procedures.

Grouping is the attribution of impact categories to one or more groups predefined in the goal and scope definition. Grouping can be done considering two optional procedures: sorting the impact categories on a nominal base and ranking the impact categories in a specific hierarchy.

Weighting is the process of converting indicator results of different impact categories with selected weighting factors or aggregating these normalized results across impact categories.
Data quality analysis is important to help determining whether significant differences exist, identify negligible LCI results and guide the interactive LCIA process. There are three types of techniques: gravity analysis, uncertainty analysis, and sensitivity analysis.

2.2.4 Life cycle interpretation

Life cycle inventory is directly related to all the other LCA phases, as shown in Figure 2. This relation must comprehend: an identification of the significant issues based on the results of the LCI and LCIA phases of LCA; an evaluation that considers completeness, sensitivity and consistency checks; and conclusions, limitations and recommendations. In general, the goal and scope definition and interpretation phases frame the study while LCI and LCIA produce information on the product system.
The goal and scope definition can be related to the interpretation phase considering: the appropriateness of definitions of the system functions, functional unit and system boundary; and limitations identified by the data quality assessment and the sensitivity analysis.
When identifying significant issues at the interpretation phase, some information from other LCA phases is required: conclusions from the other phases (related to data quality); methodological choices (e.g. allocation rules); value-choices used in the goal and scope definition; and the role and responsibilities of the different entities involved.

Evaluation intends to establish and enhance confidence in LCIA results and their reliability. The evaluation must be done considering the following three techniques: completeness check; sensitivity check; and consistency check.

Finally, the conclusions, limitations and recommendations must: identify significant issues; evaluate the methodology and results; draw preliminary conclusions and verify these consistencies with goal and scope.

2.3 **Environmental certifications of construction products**

Environmental declarations and labels are one of the tools of environmental management proposed by the ISO 14000 series and are aimed at giving information to purchasers and potential purchasers about the environmental characteristic of one product or service.

ISO 14020 (ISO, 2000) establishes nine general principles for the development and application of environmental declarations and labels. These principles intend to encourage the supply and consumption of products and services that cause less impacts in environment, between the communication of verifiable and accurate information. This standard distinguishes three types of environmental declarations:

- Type I - Environmental labelling.
- Type II - Self-declared environmental claims.
- Type III - Environmental declarations (based on LCA).

Type I environmental labelling, also known as “Ecolabels”, is supported by ISO 14024 (ISO, 2018). The principal objective of this type of declarations is the identification of products that comply with a pass/fail multi-criteria approach devised to evaluate the overall environmental performance of a product (Suttie *et al.*, 2017). This labelling programmes are voluntary and can be operated by public or private agencies and applied to national, regional or international areas. These declarations must be voluntary by nature.

Type II self-declared environmental claims can be made by manufacturers and business and the owner can declare the environmental performance of his product without quality checks, benchmarks or set criteria (Suttie *et al.*, 2017). Supported by ISO 14021 (ISO, 2016), these declarations intend to encourage the supply of products that cause less stress on environment, using verifiable, accurate and non-misleading information. Avoiding vague and ambiguous claims, the standard refers those equations like “non-polluting” or “environmentally friendly” must not be used.

Type III environmental declarations, also known as “Environmental Product Declarations” (EPDs), are guided by ISO 14025 (ISO, 2006a). These declarations provide information based on Life Cycle Assessment (LCA) method and other information related to the environmental aspects of products. These declarations can be compared with nutritional labels of food products but have as output the contributions of the product for each environmental impact category assessed (Suttie *et al.*, 2017). These declarations are voluntary and guided by a set of rules proposed by ISO 14025 (ISO, 2006a) related to its administration and operation. Type III declarations for construction products are regulated by ISO 21930 (ISO, 2007) and, at the European level, by EN 15804+A2 (CEN, 2019).

2.3.1 Environmental Product Declarations of construction materials

For construction products/materials EPDs, the core rules are defined by EN 15804. Before developing Type III environmental declarations, it is important to define the Product Category Rules (PCR).

PCR are a set of rules, requirements and guidelines required to develop Type III environmental declarations. The objectives of the core PCR are generally the provision of verifiable and consistent data related to LCA, product technical data, scenarios for the assessment of the environmental performance of buildings, and scenarios potentially related to the health of users, for the assessment of the performance of buildings. The PCR to develop EPDs for wood and wood-based products to use in construction are regulated by EN 16485 (CEN, 2014b). An EPD in the construction sector intends to assess the environmental stress of products and/or buildings and give information about the environmental profiles of products.

The comparison of EPDs of different products must be made based on the products use and functions and considering the whole life cycle of the products use. Comparisons are also possible for just one or some life cycle stages and at a sub-building level. In these cases: the same functional requirements must be used as basis for comparison; the environmental and technical performance required must be the same; the excluded process or stages and amounts of any material must be the same; and the operational aspects and impacts related to product systems must be taken into account.

The functional unit of construction products must be based on quantified functional use and performance characteristics of the product integrated in the building system and give information about the product Reference Service Life (RSL). For wood and wood-based products, the functional unit must refer the apparent density and moisture content. The RSL covers the use stage and must refer the declared technical and functional performance of the product as part of a building. RSL definition must be provided by manufacturers and take into consideration the ISO 15686 series of standards.

The declared unit of construction products is defined as a quantity of product to be used as a reference unit in an EPD and is based on one or more information modules. It provides a reference flow for which material flows are normalized to produce data expressed as a common basis. A declared unit shall be given in one or more of the next types: one item (or assembly of items); volume; mass, length, and area. For wood products, if the reference flow is not expressed in terms of mass, a conversion factor must be given.

An EPD of construction products must cover all the life cycle stages of LCA subdividing the information by modules: A1-A3; A4-A5; B1-B5; B6-B7; C1-C4; and D. There are five types of EPDs:

- Cradle-to-gate: based on information of modules A1-A3. Only the declaration of this phase is required for compliance with the standard.
- Cradle-to-gate with modules C1-C4 and module D: based on information of modules A1-A3 plus modules C1-C4 and module D.
- Cradle-to-gate with options: based on information of modules A1-A3 plus other selected optional stages of module A4-A5.
- Cradle-to-gate with options, modules C1-C4 and module D: based on information of modules A1-A3 plus modules C1-C4 and module D and plus other selected optional stages of modules A4-A5 and B1-B7.
- Cradle-to-grave and module D: covering all the phases between A1 and C4, and module D.

More information about rules for EPDs for construction products can be found in EN 15804 (CEN, 2019), and more specifically about wood and wood-based products in EN 16485 (CEN, 2014b).

2.4 **LCA of Wood and wood-based construction products**

Wood is a renewable material that is produced by natural forest ecosystems and has been used as a construction material for thousands of years around the world. From an environmental perspective, the use of wood in construction when compared with other construction materials, represents some benefits particularly in the consumption of non-renewable energy and cumulative energy demand (Werner & Richter, 2007). The carbon sequestration capacity of wood can be considered in the Global Warming Potential (GWP) and represents an advantage over other construction materials (Sathre & González-García, 2013).

Based on Takano et. al (Takano *et al.*, 2015), the wood-based materials life cycle is usually divided in four stages: product stage; construction stage; use stage and end-of-life stage. This definition is complemented with an “informative module” related to the benefits and loads beyond the product system boundary.

2.4.1 Product stage (A1-A3)

This stage, also called cradle-to-gate, gives information about the raw material supply, transport and manufacturing. In wood-based products, it covers the phases between the forest operations on trees and the packaging of the final product, inclusively.

According to FAO (2017), in terms of roundwood, in 2016, 3737 million of cubic meters were produced around the world and approximately 3.5% of this roundwood was exported (132 million of cubic meters). In terms of sawnwood, the production was approximately 468 million of cubic meters and approximately 31.4% of this wood was exported (147 million of cubic meters). These values showed the high volume of wood travelling around the world and emphasizes the importance of studying the production phases of wood life cycle.

2.4.1.1 **Raw material supply (A1) – Forest management**

2.4.1.1.1 Forest operations

The principal raw material of timber structures is wood from forests, complemented with resins, plastics for packaging, preserving products, etc. Some recycled wood-based products can be used as raw materials for other products (e.g. recycled wood used as biomass). At the European level, the literature review on EPDs and life cycle assessment studies of structural timber products identified Spruce and Pinus as the most consumed species in Europe.

The system of products derived from forest begins with the preparation of the forest area and continues with the forest management activities. González-Garcia *et al.* (2014) analyse 12 types of forest systems in Europe with different species (Willow, Poplar, Maritime pine, Douglas-fir, and Spruce) dedicated to wood production for industrial or energy uses. The authors based their study on six forest management systems (Dias & Arroja, 2012; González-García *et al.*, 2009; González-García, Bacenetti, *et al.*, 2012; González-García, Bonnesoeur, *et al.*, 2013; González-García, Krowas, *et al.*, 2013; González-García, Mola-Yudego, *et al.*, 2012). The system boundary has been divided into three stages: site preparation, stand establishment and tending, and logging operations. The functional unit defined was one cubic meter of felled fresh roundwood per year. Besides the differences between forest operations, others were identified in management regimes (light or intensive), lifespan (between 10 and 90 years), basic density (between 340 and 451 kg/m^3), yield (between 6.1 and 58.8 m^3/(ha/year)), amount of fertilizer and manure (when applicable, in kg of product per ha). The authors reported the difference in environmental results depending on tree species, management regime (level of fertilization, time of harvesting, and intensity of forest operations) and country. Operations related to logging, such as harvesting and forwarding; operations related to fertilising, such as production and fertilization; and operations related to weed control were identified as environmental hotspots.

Klein *et al.* (2015) analysed the goal, system boundaries, functional units, impact categories and involved process from 26 studies from various sites in the world. The forest stage was divided into six stages: site preparation, site tending, forestry operations, secondary process, transport and chipping. Some different beginning and endings of studies related to the system boundary were found. The system boundary usually starts at seedling/seed production, site preparation, harvesting/thinning operations, planting (by decreasing order of frequency) and ends at the plant gate or forest road (by decreasing order of frequency). The authors identified, from all the studies, 25 forest operations, being the forestry operations the ones most considered (e.g.: thinning, final felling, planting). The most common functional unit observed is the cubic meter of roundwood, with a moisture content between 12% and 140%, but in most cases between 30% and 50%. The main impact category considered was Global Warming Potential, in most cases considering carbon storage in the wood.

Based on the literature review, Klein *et al.* (2015) proposed a method for LCA of forest production based on ISO 14040 (ISO, 2006b), ISO 14044 (ISO, 2006c), and EN 16485 (CEN, 2014b). The system boundary must start with the site preparation process and end at least at the forest exit road, including all relevant processes that take place directly in the forest (primary processes) and others that are crucial in forest management. The mandatory processes considered must include site preparation, site tending, forestry operations and secondary processes. The transportation process beyond the forest road, and group chipping process (if chipping is conducted on site), can be optionally considered. The recommended functional unit is the cubic meter of product, completed with information about moisture content and wood density. In the study, the referred authors give more information about the allocation procedures and impact categories recommended.

Straka & Layton (2010) examined and assessed the relationship between forest sustainability with certification schemes and the LCA method. In this study, the authors refer that the forest’s sustainability is supported by forest certification schemes, provided by specific standards. Forest certification is performed based on the forest management practices and on their immediate impact on the environment. The Program for the Endorsement of Forest Certification schemes (PEFC) and the Forest Stewardship Council (FSC) are the two main independent non-governmental organizations that recognize forest certification schemes.

Based on United Nations data, this study identifies the amount of illegal wood extraction ratio (7.85%) and certified wood extraction ratio (26.5%). The impacts analysed were related to: machines and infrastructure; biomass burning and emissions due to land use change; biodiversity loss and effects on the pluvial system. In a cradle to forest road study, certified wood shows less impacts than non-certified wood per cubic meter of round wood on the market for the following impact categories assessed: climate change, ecosystem quality, and human health.

Ferreira *et al.* (Ferreira *et al.*, 2021), evaluated the potential environmental impact of different commercial products of Maritime pine wood (roundwood, industrial, and residual). The study assumed a cubic meter of roundwood under bark as functional unit and a cradle-to-gate approach as system boundary. LCA method was used to calculate the environmental impacts through the CML-IA methodology. The author divided the system boundary operations into: forest stands, infrastructure establishment, forest processes, pruning and thinning/final cut. The results have shown that roundwood has the highest impacts on all categories and the industrial wood has the lowest impacts. The hotspots of the production of Maritime pine roundwood occurs during the thinning/final cut operations (felling and hauling). The authors also identified that the allocation procedure followed has a considerable influence on the environmental impacts of co-products.

2.4.1.1.2 Biogenic carbon

Greenhouse gas (GHG) emissions affect climate change (IPCC, 2021) and, presently, the levels of GHG in the atmosphere have been the highest observed since the past 800,000 years. Carbon dioxide (CO_2) is one of the GHG, and thus it is important to decrease its emissions and increase its removal from atmosphere. There are three identified ways to remove carbon dioxide from the atmosphere: photosynthetic production of biomass; weathering of silicate rocks and dissolution in the oceans (Suttie *et al.*, 2017). Growing forests present a significant role on the mitigation of global warming by absorbing carbon dioxide from the air through a process of photosynthesis.

When forest grows, it absorbs carbon dioxide and, using solar energy, breaks down the CO_2 into carbon (which is fixed or stored in biomass or soil) and oxygen (which is released to the atmosphere) (Woodard & Milner, 2016). This way, forests are referred by the literature as a carbon pool.

When the trees are harvested into logs, carbon is transferred from one carbon pool, forests, to wood products, and there it stays sequestered until its disposal. In the literature, some studies refer and assume that 50% of the wood is composed of carbon. EN 16449 (CEN, 2014a) proposes a calculation method of sequestration of atmospheric carbon dioxide and refers that 100 kg of wood contain 50 kg of carbon which represents 183.5 kg of carbon dioxide. The formulation proposed by this standard is presented in equation 1.

$$Sequestred\ CO_2(kg/m^3) = \frac{Wood\ density\ (MC = 0\%)\ (kg/m^3)}{2} \times 3.67 \qquad (1)$$

The Global Warming Potential (GWP) evaluates the emissions of GHGs measured in kilograms of equivalent CO_2 per functional unit within possible time horizons (20, 50, 100 years).

Brandão *et al.* (2013) refer that the choice of a time horizon is critical: shorter time horizons increase the importance of short-lived GHGs (e.g. methane); longer time increases the importance of long-lived GHGs (e.g. CO_2). This study reviews and discusses six available methods to consider carbon sequestration and temporary storage of biogenic carbon in LCA. The authors refer that, in the decision of time horizons and carbon account methods, the merit and importance of temporary carbon storage must be considered.

Royne *et al.* (2016), based on a state-of-the-art review, indicate that most LCA studies of forest products consider carbon neutrality, which means that the amount of carbon sequestrated is the same as of carbon released during the considered phases. For one timber building as a case study, the authors compare this assumption with others such as the timing of GHG emissions and carbon sequestrations and give credit to carbon storage. The results show a high variability of results and authors recommend that the decision on the method must reflect the goal and scope of the study and the influence of decisions on the results must be calculated or estimated (sensitivity analysis).

2.4.1.2 **Transportation from forest to manufacturing place (A2)**

Even though wood was considered a sustainable material, its transportation between forest and the manufacturing place can increase the environmental impact of wood-based products. Depending on the transport distance and means available, this can be done by truck, train, ship or airplane. In transport modelling in the life cycle of products, it is important to consider the optimisation level of the transport and the density of the material transported, which affect the load capacity, fuel type and vehicle technology used in the transport (Suttie *et al.*, 2017).

Li *et al.* (2018), based on a case study in Taiwan, compared the environmental performance (embodied energy consumption and CO_2 emissions) of wood imported from different regions considering wood harvesting, transport from forest to sawmill, manufacture at sawmill, transport from sawmill to marine port, and transport from marine port to Taiwan. This study considered wood imported from the USA, Canada, China, Malaysia, Sweden, Russia, Brazil, Australia, and New Zealand. The sawmills' location and transport distance to marine port was estimated based on information from an online Sawmill database. The marine distances were determined based on Marine traffic routes. Based on embodied energy consumption and CO_2 emissions in this case study in Taiwan, the authors identified the phases of manufacture and marine transport as the ones that most influence the results. The transports between the forest and the sawmill and from the sawmill to the port, depending on the origin of wood, also influenced the results. The authors referred that this study only focused on embodied energy consumption and CO_2 emissions, and to be more conclusive more indicators should be considered.

2.4.1.3 **Manufacturing of products (A3)**

This phase of the life cycle of wood-based materials may vary considerably from one product to another. At the beginning of this phase, the wood input is roundwood, and at the end of the product manufacturing, the output for the next phase differs from product to product. According to the scope of this study, more focus on the structural products considered will be given. The common manufacturing sub-phases in wood-based construction materials are: sawing, drying, planning, sanding, grading and packaging (Suttie *et al.*, 2017) . These phases are basic for solid wood (sawnwood) manufacturing, for other products more sub-phases must be considered.

2.4.1.3.1 Sawnwood

Sawing can be generally summarized as the operation that transforms roundwood into rough sawnwood. This sub-phase starts with the log unload at the factory, followed by debarking, sawing, chipping, sorting timber by size classes, and stacking timber for drying. As co-products from this phase, beyond "green timber", there are: sawdust, chips and bark (all green products) (Milota, 2015). Ramage *et al.* (2017a) refer that approximately 50% of sawed roundwood is a co-product. This value is confirmed by Milota (2015), where the mass allocation identifies approximately 50% of sawnwood as output, 25% of chips, 10% of sawdust and 5% of bark. Co-products are used for energy production.

Ramage at al. (2017a) emphasized the importance of the drying stage in timber construction products, being related to durability, grading, gluing reception and lighter weight for transport. The most common method to dry wood is "kiln drying". This method consists of controlled heating, air circulation and humidification and ventilation in an enclosed structure (usually between 30 and 100 m^3). The efficiency of the drying program, beyond the equipment factors, is related to the species, thickness, moisture content, and end-use of the wood. For example, Ananias *et al.* (2012) identified a variation between drying one cubic meter of Radiata Pine (3 GJ) and one cubic meter of Spruce (1 GJ). According to Puettmann and Wilson (2005), this sub-phase represents approximately 90% of the cumulative energy consumption for softwood lumber.

The planning and sanding phases intend to standardize the size of timber and create a smooth surface. In the planning process, the co-products created are: sawnwood, shavings, sawdust, chips and wood flour (all dried products). Milota (2015), based on a mass allocation, attributed approximately 90% to sawnwood, 9% to shavings and 1% to the others.

To enable timber to be used as a structural product, a strength grading based on EN 14081-1 (CEN, 2016a) is required. Strength grading can be done by a visual method or by a machine. Visual strength grading is supported by a set of rules related to specific features, namely: knots on timber surface, fissures, slope of grain, density and rate of growth. Machinery strength grading evaluate the piece and assigns it to a strength class. These features are related to the wood properties and, based on that, the visual grades can be correlated to the strength grades. After grading, timber is sorted by strength and prepared for packaging.

Milota (2015) referred that packaging of solid wood is usually done by sets of timber with the same dimensions and structural classification. Usually, a clapboard is placed between elements to prevent timber elements from falling when the consumer opens the pack. Finally, the pack is covered with plastic straps and the packaged units are placed on the transport vehicle.

2.4.1.3.2 Glued laminated timber

The manufacturing of glued laminated timber is identified by Bowers *et al.* (2017) as a continuation from solid wood manufacturing. In this study, to the solid wood production, the authors added the transport from the solid wood manufacturing place to the glulam manufacturing place. The glulam manufacturing sub-stages are: end-jointing, face bonding, curing, planning, grading and packaging. In addition to these stages, the production of the resins used in end-jointing and face bonding shall be considered.

The end-jointing is done to increase the length of laminations and reduce the presence of defects. To join the ends of laminations, it is necessary to do a joint in both ends and apply a structural glue on both. The process of end-jointing must fulfil the minimum production requirements from Annex I of EN 14080 (CEN, 2013a). EN 14080 (CEN, 2013a) gives the possibility of manual or machined application of glue. Bowers *et al.* (2017) referred that glue application, pressing and gluing is usually done by the same machine.

Face bonding must also be done considering the rules of EN 14080 (CEN, 2013a). This phase starts with the planning of the phases to bond, followed by the application of glue, assemblage of the laminations, pressure application, and curing. This phase requires specific machinery for pressure application and control.

2.4.1.3.3 Laminated Veneer Lumber (LVL)

The main LVL input on manufacturing is roundwood. LVL manufacturing begins with bark removal and the cutting of logs to obtain a specific length. To reduce veneer breakage, and obtain logs easier to peel, they are preconditioned using a hot steam (Lu *et al.*, 2017). In the next stage, logs are peeled using a veneer cutter lather. Veneers are then dried through an intensive energy process (Lu *et al.*, 2017). These are then glued and assembled layer by layer. In order to obtain a better gluing quality, pressing must occur under heat conditions. After pressing, LVL is trimmed and sawed to the target dimensions. Puettmann *et al.* (2013) presented a mass allocation of approximately 90% to LVL and 10% to sawdust, panel trim, and others. Among other possibilities, the LVL produced can be used as LVL beams or as flanges for I-joist beams. Like other wood products, the last phase of LVL manufacturing is packaging.

2.4.1.3.4 I-Joist beams

The most common I-joist beams are composed of OSB in the web and LVL or solid jointed wood in the flanges. I-joist manufacturing can be divided into four stages: routing and shaping of web and flanges; assembly of I-joist and curing; sawing; and packaging. The amount of web and flange material is approximately 50% of each of I-joist materials (50% of OSB and 50% of LVL/or Solid Wood) (Bergman & Alanya-Rosenbaum, 2017).

The OSB manufacturing process can be divided into: debarking of logs; stranding, drying, screening, blending, forming, pressing, and finishing (M. Puettmann *et al.*, 2016). The manufacturing of solid jointed wood corresponds to glued laminated timber production without face bonding.

The first step in I-Joist manufacturing is the shaping of the OSB and LVL or solid jointed wood. The OSB is then cut with the dimensions required and if necessary, the web pieces are jointed. In order to join the web with the flange, the OSB web is tapered at the top and bottom edges. LVL or solid jointed wood are routed to accept the tapered OSB web. During this process sawdust is created as a co-product.

The assembly of I-joist (web-flange and web-web) is made using structural resins. The pressing directions are applied from top to bottom flange and from end to end of the beam. After the curing of the I-joist, the next phase is sawing to the dimensions required by consumers and finally packaging. Bergman & Alanya-Rosenbaum (2017) only consider the wrapping material in packaging.

2.4.1.3.5 Comparison between structural products

Pajchrowski *et al.* (2014) compared the environmental impacts of four functionally equivalent buildings with different structural products and building technologies. The analysis included: a conventional masonry building, a passive masonry building, a conventional wooden building and a passive wooden building. The main differences between masonry and wooden buildings were the composition (wood or masonry) of the structural elements. The main difference between passive and conventional buildings was the energy saving techniques prescribed during their design. The functional unit was 98.04 m^2 of residential area suitable to be used for a period of 100 years and ensuring the occupants and items protection from the harmful effects of factors external to the building. The boundary system was from cradle-to-grave, comprising the production of the building materials, prefabrication, transport to the building site, construction, use, demolition, transport and final disposal of waste. The results showed that wood was the product with the lowest environmental impacts. The authors mentioned that it was related to: the carbon neutrality of wood, the energy recovery at the end-of-life, the transport (lower weight), the flows at the building site (lower water and electric energy consumption, lower amount of construction waste produced) and the demolition stage (lower electric energy consumption).

Hill and Dibdiakoval (2016) compared the GWP and embodied energy impacts of various wood-based products: fibreboard, particleboard, OSB, LVL, glulam, and sawnwood. The functional unit was one kilogram of products, and the system boundaries were from cradle to gate (stages A1-A3). The modulations used data from EPDs and from Bath ICE database. The results showed an increase of manufacturing efforts, which means that the products with higher impacts were (decreasing order): fibreboard, particleboard, OSB, LVL, glulam, and sawnwood.

Dossche *et al.* (2018) compared the environmental impacts of various combinations of concrete, steel and wood as structural elements of a beam-floor system. The wooden floors were made of OSB and GLT beams combined with IJ and SW. The functional unit was a square meter of structural system and the equivalence between solutions was ensured by using the same loads (a permanent load of 1.5 kN/m^2 and a live load of 2 kN/m^2). Beams were simply supported, had 4.0 meters in length, and were 0.5 m and 0.6 m apart.

The system boundary was from cradle-to-grave, and the stages considered were production, transport to the building site and end-of-life. The end-of-life scenario of wood elements considered landfill (5%), incineration (75%), and recycling (20%). The results were compared per beam, per m^2, and per life cycle phase. The results showed that wood solutions had the lowest environmental impacts. Wood beams had the highest impact on agricultural land occupation. For the other categories, the GLT beams had the lowest impact. The production stage was the one with the highest impact on the environment.

Wijnants *et al.* (2019) assessed the potential of environmental impact reduction of lightweight timber frame constructions for rooftop extensions (roof and walls) by changing their composition and dimensions. The effect of using IJ instead of SW beams and adjusting the centre-to-centre distance between beams was analysed. The functional unit was 1 m^2 of wall solution and 1 m^2 of roof solution and the system boundaries were from cradle-to-gate. The SW beams were compared with IJ made of LVL flanges and an OSB web with a thickness of 10 mm. The dimensions of the SW beams were determined based on timber frame sections commonly used in Belgium and the dimensions of the IJ were based on the market offer. The results expressed in terms of “environmental costs” (Euro/m^2) showed an environmental impact reduction of up to 7% for IJ use instead of SW beams. This study also showed that increasing the centre-to-centre distance from 0.40 m to 0.60 m reduced the environmental impact from 1.5% to 3%.

Demertzi *et al.* (2020) quantified and compared the environmental impact of different structural systems for building floor’s rehabilitation. Five functionally equivalent systems, suitable for this use, were compared: timber floors; beam-and-block system; reinforced concrete slabs; steel–concrete composite slabs; and glass fibre reinforced polymer sandwich panels. The timber floor was designed with Maritime pine, a density of 600 kg/m^3 and a spacing of 0.3 m. The functional unit was 1 m^2 of floor area and the system boundaries were cradle-to-gate. The floor had a span of 4 m and the design was made considering 1.5 kN/m^2 as permanent load and 2 kN/m^2 as live load. The results showed that the timber solution had the lowest environmental impact values on all categories except for the consumption of primary renewable energy, due to the biomass consumed to produce this solution.

Hafner and Schäfer (2018) studied the interrelations between the material efficiency of building with wood and the environmental benefits of carbon storage. The authors analysed six timber buildings (Cross Laminated Timber (CLT) or timber frame constructions), four mineral-based buildings (brick and concrete buildings) and two hybrid buildings (that combined CLT and timber frame constructions in the same building). The functional unit was 1 m^2 of gross external area and the equivalence was guaranteed by thermal requirements. The system boundaries included the production (A1-A3), maintenance

(B2), replacement (B4) and waste processing (C3-C4) stages, and the benefits and loads beyond the system boundary (D). The buildings' elements analysed were the foundation, the external walls (without cladding), the internal walls and columns, the ceiling, the roof, the insulation materials and the balcony (if present). The impacts were calculated for GWP indicator and for carbon storage per gross external area. The results showed that the timber buildings have the lowest GWP impact over the life cycle. As a conclusion, the authors recommended that the material efficiency of timber products and the carbon storage capacity should always be considered in the decision-making process.

2.4.1.3.6 Adhesives

Synthetic adhesives used for wood structural products can be of three types: phenolic and amyloplastic resins (Phenol-Formaldehyde (PF); Resorcinol-Formaldehyde (RF); Phenol-Resorcinol-Formaldehyde (PRF); Melamine-Formaldehyde (MF); Urea-Formaldehyde (UF); and Melamine-Urea-Formaldehyde (MUF)); polyurethane resins of just one component (PUR); and emulsion polymeric isocyanate resins (EPI). The application of some glues must be combined with the use of a hardener to accelerate the process of resin hardening.

Wilson (Wilson, 2009) conducted a life cycle inventory of four glues: UF; MUF; PF and PRF (with hardener). Based on the USA's industry, the author presented an exhaustive and "in situ" data collection of manufacturing processes of different resins, considering 1 kg of resin as the functional unit. Messmer and Chaudhary (2015) compared the environmental impact of various glues considering: 1) 1 kg of adhesive production, and 2) the amount of adhesive/hardener required for 1 m^2 of CLT. The authors considered in this study: PUR; MUF (with hardener) and PF (with hardener). This study used data obtained from other sources and from different origins (Brazil, Sweden, the USA, Europe and Switzerland) considering transport to Switzerland. The author identified the use of hardener as a factor that increases the environmental impacts of resins.

2.4.2 Construction stage (A4-A5)

The construction stage consists of the combination and aggregation of construction materials with different functions and in different quantities in order to obtain a building (e.g. a modular house) or a constructive solution (e.g. a floor or a roof).

This stage gives information about the transport from the factory to the construction place (A4) and the construction processes (A5). The construction stage must also consider the processing and disposal of generated wastes (e.g. packaging waste) (EN 15978 (CEN, 2011a)). The transportation must consider the same indications presented in the A2 phase.

Based on the increasing prefabrication of timber structures, Takano *et al.* (Takano *et al.*, 2015) proposed a subdivision of phase A4-5 into two: A4-5: P (prefabrication process) and A4-5: O (on-site process). For on-site timber structures, the referred authors considered in the construction stage the operations of: transport by crane, lifting of elements to the final position by a crane; and application of fasteners by cordless screw drivers and drilling machines.

In this phase, the application of fasteners in construction including the fabrication of steel elements must be considered. Avenue (2012) included the timber building service life in the functional unit definition, and considered the use of steel bolts in timber in the construction phase (A5). The results for steel connectors showed a low influence on the global results.

2.4.3 Use stage (B1-B5) and operational use stage (B6-B7)

The use stage includes the period from the end of the construction until the time when the building is deconstructed or demolished. It covers the following sub-stages: use (B1), maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5). The operational use stage covers: the operational energy use (B6) and the operational water use (B7).

The structural use of timber requires a design that considers the likely conditions (structural and environmental) during the use of structures. The durability performance of timber structures is related to the natural durability of the species, preservative treatments applied, and water exposure during the service life (Ramage *et al.*, 2017a).

During the life cycle of a building, Robertson *et al.* (2012) consider the use of a wood sealer applied to exterior exposed wood, repeated every two years. Pal *et al.* (2017) refer that, for structural timber and for reinforced concrete, there is no need to assume replacement and maintenance during a life cycle of 50 years (internal use). John *et al.* (2009) consider the use of structural timber (LVL) and refer that, for a period of 60 years, there is no need of maintenance, but the product was purchased with a sealer coat applied. (Peñaloza *et al.*, 2016) only consider the phase B6 in a “timber building” life cycle when compared with a “concrete building”. This phase only considers the heating energy. Takano *et al.* (Takano *et al.*, 2015) assumed that timber products do not need any use operation for 50 years.

Norwegian Wood Industry Federation (2015b) refers that, in a normal scenario, structural timber does not need maintenance, repair, replacements, changes during refurbishment, or any operational energy or water consumption. When timber is used as a structural material and the durability is taken into account in the design, there is no need of use operations during the life cycle of structures. When timber is used outdoors, and preservative treatments are applied, the exfoliation of chemical products used for treatment and its reapplication must be considered.

2.4.4 End-of-life stage (C1-C4)

The end-of-life stage covers the next sub-stages: deconstruction/demolition, transport to waste treatment, waste processing and preparation for recycling or disposal. In deconstruction (C1), the process and the equipment used are similar to those of the construction stage (e.g. crane). In this phase, transport (C2) to the disposal or recycling company must be considered. Transportation must be modelled based on the type of means used and on the density of the product(s). For the end-of-life of wood structures, Jungmeier *et al.* (2018) presented five alternatives for the end-of-life of timber products: reuse as a material, burn for energy use, burn without energy use, landfill, and natural decomposition. Based on Directive 2008/98/EC (European Parliament, 2008), Jungmeier *et al.* (2018) and Ramage *et al.* (2017a) identified three main options for the end-of-use of wood products: reuse, burn and landfill.

The end-of-life for timber structures must be considered for the main product and all waste generated (or co-products) during the timber structures' life cycle (e.g. wood harvesting waste; sawdust).

Reuse must be a priority for the end-of-use of timber elements. Cascade utilization can be defined as an efficient utilization of resources by using wastes and recycled materials for material use and it is identified by the European Commission as a valuable tool in the "Strategy for forest-based industries". In timber life cycle, the cascading use of timber is studied and has proved to reduce the environmental impacts (Höglmeier *et al.*, 2014, 2015, 2017). Timber can be reused as a product (intact or re-sized) or a material (developing new products). In Germany (the main producer of waste wood in Europe) (Garcia & Hora, 2017), wood waste is separated in five categories (based on the chemicals products applied in the wood, e.g. glues, preservative treatments), and in possible re-application as a material. This classification requires construction wood' wastes to be treated before re-using or cascading and actually some companies prefer burning these wastes to produce energy. The consideration of reuse or recycling of wood is related to the D phase of the life cycle (benefits and loads beyond the product system boundary).

Burning for energy recovery or energy supply with wood products is possible through direct combustion or conversion into gaseous, liquid or solid fuel (biomass). Ramage *et al.* (2017a) divided wood for burning into two groups: clean wood and contaminated wood. Clean wood can be burned by normal power stations or private stoves, while contaminated wood (e.g. treated, glued, or painted wood, etc.) can only be used for energy generation in special stations. Taylor *et al.* (2005) identified five main end-of-life options in the Australian context: fuel briquettes and pellets production; use as coal for power stations; use as coal in cement kilns; cogeneration by increasing the amount of other fuels (e.g. bagasse); and biomass for power stations. FAO (2017) highlights the increase of pellets production around the world when compared with other possibilities as coal production and use as wood fuel.

Landfill must be the last choice of all timber end-of-life possibilities (Ramage *et al.*, 2017a). Some governments try to ban wood from landfills, increasing the energy recovery, material recovery and recycling.

2.4.5 Preservative treatments

Some studies regarding the use of LCA to calculate the environmental impacts of treated wood, including its comparison with competing alternatives (for the same structural function), were found in the literature and are described next.

Bolin and Smith (2011) compared the environmental impacts of borate-treated wood structure with galvanised steel framing for a UC 2 exposure during a service life of 75 years. Three cases were considered in this comparison: 2.36 m^3 of structural element; 30.5 m of a wall framing solution; and a complete solution for a house (a surface of 206.7 m^2 and a perimeter of 61.0 m). The system boundary of the LCA of the wood-treated elements considered four main stages: wood production, wood treating, use, and disposal. The production and application of preservative treatments were modelled as part of the wood treating stage. At the use stage, maintenance operations and emissions that occur during the service life were not considered. At the end-of-life stage, it was assumed that the treated-wood elements were landfilled. The results showed that the greenhouse gas emissions, fossil fuel use, acidification, ecological toxicity, smog forming potential, and eutrophication of the borate-treated house are less than 0.1% of those of a galvanised steel house.

In another study by Bolin and Smith (2011b), they compared the environmental impacts of pentachlorophenol-treated wood with steel and concrete utility poles, for a UC 4 exposure for 60 years. Wood utility poles were treated with a 16 kg/m^3 retention rate. The functional unit was one pole, and the system boundaries cover four main stages: wood production, wood treating, use stage, and final disposal. The treating stage comprised the production and application of preservative products. During the use stage, emissions of pentachlorophenol and VOCs to air and pentachlorophenol to soil were estimated based on experimental studies of these products. They also considered three in-situ maintenance operations with the application of a surface product composed by copper, borate, petroleum, water and a mineral filler. A mix of three scenarios were considered at the end-of-life: reuse (47%), incineration for energy recovery (21%), and landfill (32%). The authors considered that wood combustion destroys all active substances retained in wood, except for chlorine in pentachlorophenol, which is emitted as hydrochloric acid. Pentachlorophenol not leached during the product use stage was allocated as a soil emission in the landfill phase. The results showed that the greenhouse gas emissions, fossil fuel use, acidification, water use, eutrophication and ecological toxicity impact values of pentachlorophenol-treated poles are less than those of steel poles and concrete poles. The smog impact is greater for pentachlorophenol-treated poles than for both concrete and steel poles.

Tsang *et al.* (2014) compared the environmental impacts of three penetrating preservative treatment alternatives in a seedbed for a UC 4 exposure for 20 years. They compared two preservative products: alkaline copper quaternary and micronized copper quaternary, the former assuming a penetrating rate of 6.4 kg/m^3 (ACQd) and the latter with penetrating rates of 5.4 (MCQ0.40) and 6.4 kg/m^3 (MCQ). The functional unit was 0.0157 m^3 of treated wood and the system boundaries covered the following stages: manufacturing of preservative products, production of wood elements, application of preservative products, use and disposal. The emissions from leaching of copper and didecyldimethylammonium chloride (DDAC) during the use phase were estimated from mean values identified in other studies reviewed. They excluded landfill emissions due to lack of information regarding landfill leaching rates. The results showed that the MCQ treatment had the lowest environmental impacts for all impact categories assessed, except for global warming potential in which ACQd treated wood had the lowest environmental impact.

Tsang *et al.* (2014) compared the environmental impacts of timber treated with various products, such as MCQ, ACQ, water-borne copper naphthenate (CN), oil-borne copper naphthenate (CN$_O$), water-borne copper quinolate (CQ), and water-borne zinc naphthenate (ZN). MCQ and ACQ products were applied by pressure and their retention ratio was 5.44 kg/m^3 and 6.40 kg/m^3, respectively. CQ, CN, CN$_O$ and ZN were applied on the surface and their retention ratio was 2.08 kg/m^3. The functional unit was defined as 100 m^3 of treated timber. The system boundary was from cradle-to-gate and considered the raw material extraction, material processing, product manufacture, and product use stages. MCQ and CN were the treatments that had the best environmental performance. In contrast, CQ was the treatment with the highest environmental impacts.

2.5 Review of EPDs of wood products

This section made a review of European EPDs of SW, GLT, LVL and IJ using the NativeLCA (Silvestre *et al.*, 2015) methodology. The NativeLCA methodology intends to provide consistent guidelines that can be used to select LCA datasets to be used as generic data in a national context. This methodology consists of the collection, characterization, qualification and selection among available datasets and comprises four steps:

i) Goal and scope definition of the LCA study,
ii) Collection and description of available LCA datasets,
iii) Comparison of the datasets impact values,
iv) Choice of dataset to be used as generic data for a national context.

This methodology is applied in this study to review the LCA procedures and technical data provided in EPDs of SW, GLT, LVL and I-Joists and to determine the European Reference Values (ReVa) of SW, GLT, LVL and I-Joists products.

2.5.1 Goal and scope definition of the LCA study

The first step of NativeLCA methodology is the goal and scope definition of the LCA study/database. The main goals are the review of EPDs of SW, GLT, LVL and I-Joists produced according to EN 15804 (CEN, 2019) and the determination of the ReVa for SW, GLT, LVL and I-Joists products.

The scope definition of this study follows the core rules of EN 15804 (CEN, 2019) and EN 16485 (CEN, 2014b) standards. The functional unit (FU) is 1 m^3 of SW, GLT and LVL and 1 linear meter of I-Joists. This study is made for the production stage (A1-A3), construction stage (A4-A5), use stage (B1-B7) and end-of-life stage (C1-C4) and benefits and loads beyond the system boundary (module D). The cut-off and allocation rules shall follow the requirements of the Life Cycle Impact Assessment (LCIA). Indicators are the environmental impacts quantified in the EPDs for SW (softwoods and hardwoods), GLT, LVL and I-Joists products.

2.5.2 Collection and description of available data sets

The second step of NativeLCA consists in the identification and characterisation of the LCA datasets, including data quality information and meta-data. The search for EPDs was made in the ECO EPD programmes registered in February, 2019.

A total of 28 EPDs were identified, grouped by product type: 14 EPDs for SW products, 9 EPDs for GLT products, 2 EPDs for LVL products and 3 EPDs for I-joists products (Table 1). All the EPDs found are from European EPD programmes. Three SW EPDs

(SW4; SW9 and SW10) and one GLT EPD (GLT5) consider the production of more than one product. For these EPDs, the data are analysed separately. This results in 18 datasets of SW products, 10 datasets of GLT products, 2 datasets for LVL products and 5 datasets for I-Joists products. A terminology is proposed in Table 1 for the datasets of various products.

Table 1 – Terminology adopted for various datasets studied

Terminology	Reference
SW 1	(Norwegian Wood Industry Federation, 2015a)
SW 2	(Norwegian Wood Industry Federation, 2015b)
SW 3	(Rubner Holding AG -S.p.A., 2018b)
SW 4a	(Überwachungsgemeinschaft Konstruktionsvollholz E.V., 2017)
SW 4b	(Überwachungsgemeinschaft Konstruktionsvollholz E.V., 2017
SW 5	(Fritz EGGER GmbH & Co. OG, 2018a)
SW 6	(Fritz EGGER GmbH & Co. OG, 2018b)
SW 7	(Fritz EGGER GmbH & Co. OG, 2018c)
SW 8	(Rubner Holding AG -S.p.A., 2018c)
SW 9a	(Forest and Wood Products Australia Ltd, 2017c)
SW 9b	(Forest and Wood Products Australia Ltd, 2017c)
SW 10a	(Forest and Wood Products Australia Ltd, 2017b)
SW 10b	(Forest and Wood Products Australia Ltd, 2017b)
SW 10c	(Forest and Wood Products Australia Ltd, 2017b)
SW 11	(Wood for Good, 2013a)
SW 12	(Wood for Good, 2013c)
SW 13	(Wood for Good, 2017)
SW 14	(Wood for Good, 2013e)
GL 1	(Moelven Töreboda AB, 2016)
GL 2	(Sorlaminering AS, 2014)
GL 3	(Joint-Stock Company “Sokolsky DOK,” 2018)
GL 4	(Rubner Holding AG -S.p.A., 2018a)
GL 5a	(Forest and Wood Products Australia Ltd, 2017a)
GL 5b	(Forest and Wood Products Australia Ltd, 2017a)
GL 6	(Wood for Good, 2013b)
GL 7	(Studiengemeinschaft Holzleimbau e.V, 2013)
GL 8	(Studiengemeinschaft Holzleimbau e.V & Überwachungsgemeinschaft Konstruktionsvollholz e.V., 2018)
GL 9	(Schilliger Holz AG, 2018)
IJ 1	(Masonite Beams AB (Byggma ASA), 2015)
IJ 2	(James Jones & Sons Ltd, 2017)
IJ 3	(Metsä Wood, 2015b)
IJ 4	(APIBOIS, 2018b)
IJ 5	(APIBOIS, 2018a)
LVL 1	(Wood for Good, 2013d)
LVL 2	(Metsä Wood, 2015a)

For each dataset, the following information was analysed:

- Country of publication,
- Year of publication,
- Sampling procedures,
- Functional/declared unit,

- Density of the product,
- Moisture content of the product,
- Life cycle stages considered.
- Number of companies accounted,
- Cut-off rules,
- Allocation rules,
- Background database,
- Temporal representativeness of the study,
- Geographical coverage,
- Technological level,
- Carbon account methodology,
- Amount of biogenic carbon per FU.

When applicable, product specific data was also analysed (such as wood species and strength class). All EPDs assessed are externally reviewed and the comparability is ensured following EN 15804. The general data collected for SW EPDs are presented in Table A.1 of Annex A, and for GLT, LVL and I-Joists EPDs are presented in Table A.2 of Annex A.

The second step of NativeLCA also includes a consistency and representativeness verification of each foreign dataset. All the datasets are obtained from EPDs externally evaluated by companies that perform an independent verification of data in accordance with ISO 14025 (ISO, 2006a). The meta-data analysis of consistency and representativeness products are presented in Table A.3 and Table A.5 for SW, and in Table A.4 and Table A.6 for GLT, LVL and IJ.

The analysis of consistency and representativeness meta-data showed that:
For SW products:

- Two EPDs (SW9 and SW10) belong to Australian companies. The remaining EPDs belong to European companies,
- Five EPDs (SW3, SW5, SW6, SW7 and SW8) are individual EPDs. In contrast, the other EPDs belong to groups of producers,
- The functional unit is one cubic meter of product for all EPDs,
- Four datasets (SW 10a, SW10b, SW 10 c, and SW12) are made for hardwoods. All the other datasets are made for softwoods,
- Three datasets (SW6, SW10c and SW11) assessed “green wood” products. The SW7 and SW10a datasets correspond to the dried planed products assessed for SW6 and SW10c datasets, respectively,

- Three datasets (SW5, SW9a and SW10a) assessed rough wood (unplaned wood). The SW7, SW9b and SW10b correspond to the planed products of SW5, SW9a and SW10a, respectively,
- The two highest densities of planed dried products are registered for hardwood (SW10b - 735 kg/m^3) and softwood (SW9b - 551 kg/m^3) Australian products. The smallest density registered is 420 kg/m^3 (SW2),
- All the datasets assessed the production (A1-A3) stages. These stages cover the forest grown, transport of wood from forest to the sawmill and sawmilling of wood,
- Five datasets assessed construction (A4-A5) stages. The operations considered the transport of sawnwood from factory to the construction place for A4 stage. The datasets that considered the stage A5 assumed a 5% wastage during installation and an electricity consumption of 1 MJ per FU,
- Two datasets considered the use stages (B1-B7). Despite considering the use stage, these datasets do not consider any operation during the use of structure,
- Fifteen datasets considered the end-of-life (C1-C4) stages. The operations most considered in the end-of-life stage comprise the energy recovery, followed by incineration, recycling and landfill,
- All the datasets assessed the module D. The majority of datasets consider the benefits of energy recovery from wood products,
- The wood species assessed in datasets are: Pinus (14 datasets), Spruce (12 datasets), Larch (5 datasets), Douglas fir (3 datasets), Ash (1 dataset), Beech (1 dataset), Poplar (1 dataset), Oak (1 dataset), and Australian native softwood and hardwood species,
- Two datasets consider the use of the glues PUR and MUF for finger joints production (SW4b and SW8),
- Nine datasets refer the limitations of beams’ dimensions. The height dimensions vary from 0.012 to 0.6 [m]. The width dimensions vary from 0 to 0.35 [m]. The length dimensions vary from 0 to 50 [m],
- Five datasets (SW2, SW3, SW4a, SW4b and SW8) identified C24 as the structural class of products,
- All the datasets consider the biogenic carbon in GWP indicator. Some datasets do not refer the methodology used to calculate the amount of biogenic carbon per functional unit and the amount of biogenic carbon per functional unit,
- The most adopted methodology is the methodology supported by EN 16449 (CEN, 2014a). The amount of biogenic carbon varies from 660 to 1100 kgCO$_2$/FU.

For glulam products:

- One EPD (GL5) belongs to Australian companies. The remaining EPDs belong to European companies,
- Five EPDs (GL1, GL2, GL3, GL4 and GL9) are individual EPDs. The other EPDs belong to groups of producers,
- The functional unit is one cubic meter of product for all EPDs,
- One dataset (GL5b) is made for hardwoods. All the other datasets consider softwoods,
- All the EPDs consider products prepared to be used in construction (dried and planed),
- The minimum density is 424 kg/m^3 and the maximum density is 674 kg/m^3. The maximum density is registered for hardwood glulam produced in Australia. The second highest density (621 kg/m^3) is registered for softwood produced in Australia. The lowest density is registered for Schillinger glulam produced in Switzerland,
- All the EPDs consider the production stages (A1-A3). The production stages cover the forest grown, transport of wood from forest to the factory, and operations of production of glulam (such as finger jointing, planning, gluing, pressing, and trimming),
- Construction stages (A4 or A5) are considered in 6 datasets. The datasets that assessed the A4 stage considered the transport of glulam to the construction site. The datasets that considered the A5 stage exclusively cover the disposal of product packaging,
- End-of-life stages (C1-C4) are considered in 8 datasets. The operations most considered in the end-of-life stage comprise the energy recovery, followed by incineration, recycling and landfill,
- The reuse/recycle/recovery stages (D) are considered in 8 datasets. Most datasets consider the benefits of energy recovery from wood products,
- The wood species assessed in datasets are: Spruce (6 datasets), Pinus (6 datasets), Larch (3 datasets), Douglas fir (3 datasets), Fir (2 datasets), Eucalyptus (1 dataset), Australian native softwood and hardwood species, and other species of wood not referred,
- The glues considered if the production of glulam is: PUR (6 datasets), MUF (6 datasets), PRF (5 datasets), EPI (2datasets) and LIM (1 dataset). The number of glues per FU varies from 0.3 to 2.5 %,
- Four datasets refer the limitations of beams' dimensions. The height dimensions vary from 0.10 to 2.4 [m]. The width dimensions vary from 0.06 to 0.28 [m]. The length dimensions vary from 0 to 50 [m],
- Two datasets identified the class GL24h as the structural class of products (GL4 and GL7). One dataset refers that the products can be from six structural classes

(GL24c, GL28c, GL32c, GL24h, GL28h, and GL32h). One dataset is made for glued solid timber (GL8) and the structural classes are related to sawnwood classes (C18, C24 and C30),

- All the datasets consider the biogenic carbon in GWP indicator. Some datasets do not refer the methodology used to calculate the amount of biogenic carbon per functional unit and the amount of biogenic carbon per functional unit,
- The most adopted methodology is the methodology supported by EN 16449 (CEN, 2014a). One dataset considers that 49 % of dry matter of wood is carbon. The amount of biogenic carbon varies from 755 to 1118 kgCO_2/FU.

For I-joist products:

- All the EPDs belong to European companies,
- Three EPDs (IJ1, IJ2 and IJ3) are individual EPDs. The other EPDs belong to a group of manufacturers,
- Two functional units are identified: 1 linear metre of product and 1 kg of product. For comparison, the density of product is used to convert the environmental impacts related to a FU of 1kg on environmental impacts related to 1 lm,
- The minimum density is 3.8 kg/lm and the maximum density is 11.4 kg/lm,
- All the EPDs consider products prepared to be used in construction (dried and planed),
- All the EPDs consider the production stages (A1-A3). The production stages cover forestry operations, production of glues, production of flange products, production of web product, transport of products to the factory, and assembling of products,
- Construction stages (A4 or A5) are considered in 3 datasets. The stage A4 assumed the transport of products to the construction stage and the stage A5 assumed 5% wastage during installation and an electricity consumption of 1 MJ per m^3,
- End-of-life stages (C1-C4) are considered in 3 datasets. The reuse/recycle/recovery stages (D) are considered in 3 datasets,
- There is no reference to the timber species considered in the production of I-Joist beams,
- The glues considered if the production of I-Joist beams is: PUR (2 datasets), and UF (1 dataset). Only one EPD refer the amount of glue used per FU (IJ2) – 1.5%,
- The limitations of dimensions are not referred in EPDs,
- The web materials considered are OSB/3 in all datasets, and the flange materials are Sawnwood (4 datasets) and LVL (1 dataset),
- All the datasets consider the biogenic carbon in GWP indicator. Some datasets do not refer the methodology used to calculate the amount of biogenic carbon per

functional unit and the amount of biogenic carbon per functional unit. The most adopted methodology is the methodology supported by EN 16449 (CEN, 2014a). One EPD consider the methodology proposed by PAS2050. The amount of biogenic carbon varies from 3.89 to 14.70 kgCO$_2$/FU.

For LVL products:

- All the EPDs belong to European companies,
- One EPD (LVL2) is an individual EPD. The other EPD belongs to one group of manufacturers,
- The functional unit is one cubic meter of product for all EPDs,
- The minimum density is 475 kg/m^3 and the maximum density is 488 kg/m^3,
- All the EPDs consider products prepared to be used in construction (dried and planed),
- All the EPDs consider the production stages (A1-A3). This stage covers the forest operations, production of glues, transport of products to the factory gate and production of LVL (such as finger jointing, planing and gluing, pressing and finishing,
- Construction stages (A4 or A5) are considered in 1 dataset. There is no reference in the EPD about the operations considered,
- End-of-life stages (C1-C4) and reuse/recycle/recovery stages (D) are considered in 1 dataset. This stage considered different scenarios for end-of-life: recycling, energy recovery, and landfill,
- There is no reference about the timber species considered in production of LVL beams,
- The glues considered in the production of I-Joist beams are: PUR (2 datasets), and UF (1 dataset). Only one EPD refer the amount of glue used per FU (IJ2) – 1.5%,
- Only one EPD refers limitations of beams’ dimensions. The height dimensions vary from 0.03 to 0.09 [m]. The width dimension is 0.045 [m] and the length dimension is 12 [m],
- All the datasets consider the biogenic carbon in GWP indicator. Some datasets do not refer the methodology used to calculate the amount of biogenic carbon per functional unit and the amount of biogenic carbon per functional unit.
- The methodology adopted is the methodology supported by EN 16449 (CEN, 2014a). The amount of biogenic carbon presented is 789 kgCO$_2$/FU,
- One dataset did not consider the packing stage (LVL1).

From the Table A.3 it can be seen the following for all products:

- The cut-off and allocation rules are done in accordance with EN 15804+A2 (CEN, 2019) for all datasets,

- Not all datasets refer the cut-off rules. The most considered cut-off rule excludes the raw materials and flows with less than 1% of the total mass,
- In most cases, the allocation rules consider the mass and volumetric allocation for products and co-products. When the amount of a co-product is reduced it is considered an economic allocation,
- The background data most considered is the Gabi database followed by the Ecoinvent database,
- The temporal representativeness covers the years between 2008 and 2017,
- The geographical coverage depends on the holder of an EPD. When the holder of an EPD is one company, the EPD covers the production sites of that company. When the holder of an EPD is a group of producers, the EPD covers the company's production sites members of this group of producers,
- The technological level is referred as the typical technology of the country under study.

2.5.3 Calculation and comparison of ReVa impact values

In the third stage of NativeLCA, ReVa were calculated and compared for each environmental impact category, in order to identify them for each product. The methodology proposed three scales for ReVa: national, European and foreign (other countries in Europe). The datasets can be: site-specific data from national LCA studies; national average LCA datasets (national ReVa); national group of manufacturer's EPD (national ReVa); national single manufacturer's EPDs (national ReVa); European single manufacturer's EPDs (foreign ReVa); European group of manufacturers' EPDs (foreign ReVa), Country-specific average LCA dataset (foreign ReVa); European average LCA dataset (foreign ReVa); and unit process generic LCA data. According to Silvestre *et al* (2015), ReVa shall be calculated as a weighted mean based on the production volumes that corresponds to each dataset. If this information is not available, ReVa shall be calculated as a weighted mean according to the number of companies.

European ReVa was calculated for SW, GLT, LVL and I-Joist products based on the European single manufacturer's EPD (foreign ReVa) and European group of manufacturers' EPDs. EPDs from countries outside Europe are not considered in the determination of European ReVa (SW9, SW10, and GLT5).

SW ReVa was calculated with four European single manufacturers' datasets and five European groups of manufacturers' datasets. GLT ReVa was determined based on five European single manufacturers' datasets and three European groups of manufacturers' datasets. LVL ReVa was calculated with one European single manufacturer's dataset and one European group of manufacturers' datasets. I-Joists ReVa was determined based on three European single manufacturers' datasets and two European groups of manufacturers' datasets. Since the EPDs under study do not make reference to the volume of production, the ReVa mean and standard deviation were calculated from the weighted average of the datasets considering the number of companies.

EPDs that do not specify the number of companies that are represented (SW11, SW12, SW14, GLT6 and LVL1) were excluded from the calculation of the ReVa. However, despite not referring the number of companies and production volumes, these datasets are representative of the United Kingdom's SW, GLT and LVL production and consumption mix. They are assumed as representative of the United Kingdom's industry of softwoods (SW14) and hardwoods (SW12), GLT (GLT6) and LVL (LVL1). SW datasets that contemplate greenwoods are also excluded from the calculation of ReVa (SW6 and SW11). ReVa of SW products was determined based on the SW1, SW2, SW3, SW4a, SW4b, SW5, SW7, SW8 and SW13 datasets. ReVa of GLT products are determined based on the GLT1, GLT2, GLT3, GLT4, GLT7, GLT8 and GLT9 datasets. ReVa of I-Joists products was determined based on the IJ1, IJ2, IJ3, IJ4 and IJ5 datasets. ReVa of LVL was determined based on the LVL1 dataset. As all the datasets considered in SW and GLT ReVa calculation are for softwood products, so the SW and GLT ReVa are representative of softwood species. The ReVa of SW, GLT, LVL and I-Joists products are representative of 229, 75, 1 and 13 European companies, respectively.

As the production stage is the only stage to be assessed in all datasets, the ReVa is just calculated for this stage (A1-A3). The environmental impact categories considered are those assessed in EPDs: global warming (GWP), ozone depletion (ODP), photochemical ozone formation (POCP), acidification (AP), eutrophication (EP), mineral and fossil resource depletion (ADPE), and non-fossil resource depletion (ADPM).

The environmental impacts of each SW, GLT, IJ and LVL datasets assessed and excluded in the calculation of ReVa of SW, GLT, IJ and LVL are given in A-7 of Annex A. The ReVa of SW, GLT, IJ and LVL and the United Kingdom's representative values for SW, GLT and LVL are shown in Table 2.

The relative environmental impacts of SW, GLT and LVL ReVa are compared in Figure 6. In addition, the representative data of the softwoods, hardwoods, glulam and LVL produced in the United Kingdom are also shown in Figure 6. IJ ReVa was excluded from this analysis because the FU of IJ EPDs (one linear meter) differs from the FU of SW, GLT and LVL (one cubic meter).

Table 2 – ReVa and UK impacts for SW, GLT, LVL and IJ products

	GWP	**ODP**	**POCP**	**AP**	**EP**	**ADPM**	**ADPE**
Units	kg CO_2 Eq.	kg CFC11 Eq.	kg ethene Eq.	kg SO_2 Eq.	kg PO_2^{3-} Eq.	kg Sb Eq.	MJ
SW ReVa	-6,68E+02	7,72E-06	4,33E-02	3,98E-01	8,50E-02	3,21E-04	7,91E+02
GLT ReVa	-6,44E+02	1,38E-05	5,10E-01	3,23E-01	1,39E-01	7,10E-04	1,96E+03
LVL ReVa	-6,55E+02	1,92E-08	9,20E-02	1,08E+00	2,20E-01	8,00E-04	2,61E+03
IJ ReVa	-9,34E+00	2,51E-07	1,06E-03	1,82E-02	3,12E-03	4,03E-06	4,42E+01
SW Soft UK	-6,46E+02	4,06E-09	6,38E-02	7,55E-01	1,31E-01	1,05E-05	1,75E+03
SW Hard UK	-8,78E+02	3,70E-08	5,95E-01	1,13E+00	1,48E-01	1,82E-05	2,53E+03
GLT UK	-4,88E+02	1,66E-08	8,90E-02	1,03E+00	1,82E-01	8,42E-05	3,86E+03
LVL UK	-5,37E+02	1,90E-08	1,05E-01	1,15E+00	1,71E-01	5,81E-05	3,54E+03

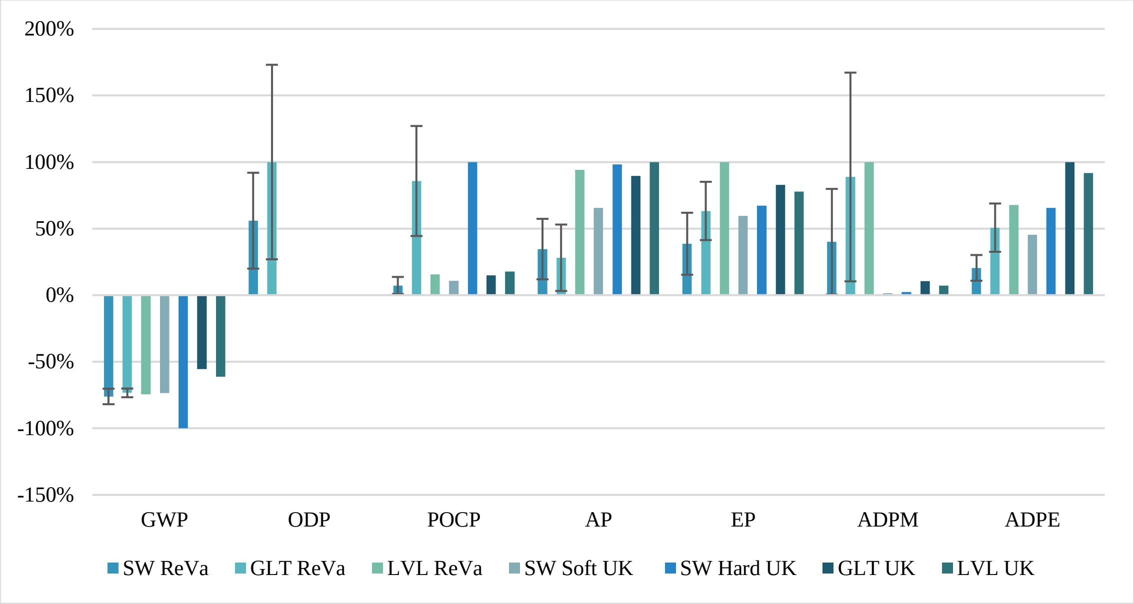

Figure 6 – Comparison of ReVa and UK impacts for SW, GLT and LVL products

In Figure 6, it can be seen that, for the GWP category, the GLT from the UK had the highest impacts and hardwood from the UK had the lowest impacts. The lowest impacts of hardwoods from the UK were related to the carbon dioxide sequestered per product (the hardwood from the UK had the highest carbon sequestered per cubic meter of product). The standard deviation of SW and GLT ReVa was 5.8% and 3.3% of the relative impact values, respectively.

For the ODP category, the SW and GLT ReVa impacts were higher than in other scenarios (variance was higher than 50 % for SW and 95 %for GLT). Standard variance of SW and GLT ReVas was 36.0% and 73.0% of the relative impact values, respectively. Hardwoods from the UK had the highest impacts on POCP followed by the GLT ReVa scenario. The variance between those scenarios and the other scenarios was higher than 65.0% of the relative impact values. Standard variance of SW and GLT ReVas was 6.4% and 41.3% of the relative impact values, respectively.

SW and GLT ReVa were the scenarios that showed the lowest impacts on the AP category. LVL from the UK had the highest impacts followed by hardwood from the UK and LVL ReVa. Standard deviation of SW and GLT was 22.7% and 24.9% of the relative impacts, respectively. For EP, LVL ReVa had the highest impacts followed by GLT and LVL from the UK. SW Reva had the lowest impacts followed by softwood from the UK, GLT ReVa and hardwoods from the UK. Standard deviation of SW and GLT ReVas was 23.3% and 21.9% of the relative impact values, respectively.

For ADPM, the highest impact was noted for the LVL ReVa scenario followed by GLT and SW ReVas. Softwood from the UK had the lowest impacts followed by hardwood, LVL and GLT from the UK. The standard deviation of SW and GLT ReVas was 39.7% and 78.4% of the relative impact values, respectively. ReVa scenarios had higher impacts than the UK scenarios on all products. GLT and LVL from the UK had the highest impacts on the ADPE category. SW ReVa had the lowest impacts followed by softwoods from the UK. The standard deviation of SW and GLT ReVas was 9.7% and 18.1% of the relative impact values, respectively.

2.6 **Conclusions**

This chapter performed a literature review of the rules and procedures given by ISO and European standards for calculation of environmental impact with LCA methodology. The main procedures were identified for LCA stages: goal and scope definition, LCI, LCIA and interpretation. In the goal and scope stage, it must be identified: the functional unit or declared unit, the system boundary, allocation procedures, cut-off criterion, data collection procedure, and data quality requirements. The LCI stage consists of the collection of data, calculation, and allocation procedures. The LCIA stage consists of the evaluation of the significance of the potential environmental impacts obtained using LCI data. This stage is composed by mandatory and optional phases. The main objectives of the interpretation stage are the evaluation of the completeness, sensitivity, consistency of results; and the identification of the conclusions, limitations and recommendations of the LCA.

The ISO standards identified three types of environmental certification: environmental labelling, self-declared environmental claims, and environmental product declarations. The latter provide information based on LCA method and other information related to the environmental aspects of products. Those declarations were used to calculate the European ReVa of SW, GLT, LVL and IJ products. The results showed that LVL and SW were the products with the highest and lowest impacts in the majority of the impact categories, respectively. The highest standard deviations of results were noted for GLT for ODP, ADPM and POCP categories.

The literature review of LCA studies of wood-based products identified that the life cycle of products for structural use can be divided into: forest management, transport of roundwood from forest to the sawmill, production of SW, GLT, LVL or IJ, transport of products to the building place, construction, maintenance, deconstruction, transport of products to the end-of-life facilities, and end-of-life operations. The life cycle of preserved products complements the life of wood-based products with the operations of: production of preservative products, application of preservative products, and leaching and maintenance of preservative products.

3 TIMBER STRUCTURES

3.1 Structure of wood

Wood is a natural material obtained from trees that grow in forests in rather variable conditions throughout the world. For thousands of years human societies used wood as a construction material and some of the earliest constructions lasted until today (e.g. Horyuji Temple in Nara, Japan).

In their molecular structure, wood is essentially composed of cellulose, hemicellulose lignin and extractives (Ramage *et al.*, 2017a). These components give wood its stability, durability and physical/mechanical properties. During wood processing (e.g. drying), some of the components may change and, consequently, the wood properties as well. The principal directions of wood are usually assumed as: axial; tangential and radial.

The growth of a tree results from a cellular division activity at the top of the plant and transversally to the trunk. The new cells transversally to the trunk appear on the periphery, so the oldest wood is located in the centre of the trunk, near the pith (Figure 7). Every year, cells form a new growth ring composed of a dark and slim part (latewood) and a thick and light part (earlywood).

In the macroscopic anatomy of wood, with a few exceptions, it is possible to identify the sapwood and the heartwood. Heartwood is the area in the centre of the trunk, it is constituted by older dead cells, and its main function is to give the tree self-supporting resistance. Sapwood is the remaining area until the bark and is constituted by living cells that conduct the sap and store nutrients (Cachim, 2014). The distinction between sapwood and heartwood is relevant since they have different properties, namely in terms of mechanical strength and stiffness, durability and visual appearance.

Trees that produce wood can be divided into two main groups: hardwood (angiosperms) and softwood (gymnosperms). The main biological difference between them is related to botanical properties: seeds protected by an ovary (hardwood) or not (softwood), resulting in differences in characteristics, properties and behaviour of wood.

In the Northern Hemisphere, softwood is predominant in comparison to hardwood, which results in their predominant use in construction. Hardwood is normally used in construction when more bearing capacity is required perpendicularly to the grain (Cachim, 2014).

In Europe, the construction market uses mostly softwood species for structural purposes and, therefore, this work will focus mostly on softwood.

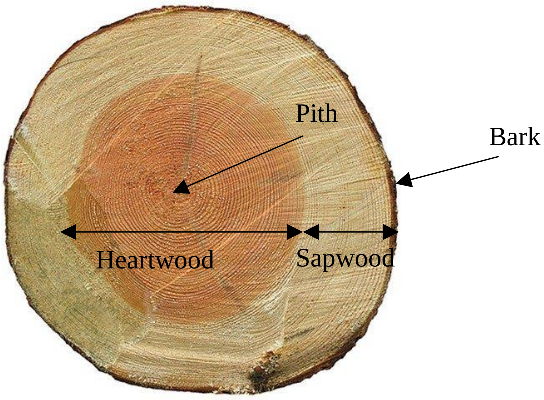

Figure 7 - Tree cross-section

3.2 **Wood properties**

3.2.1 Visual properties

In terms of the tree structure, several visual/physical characteristics can influence the mechanical properties of wood, such as knots, twists (slope of grain), reaction wood, density (rate of grow) and resin pockets (Figure 8). After sawing, it is important to consider the wane and warp, and the fissures.

Knots appear during the tree growth, initially as a branch bud that, if cut, dries and the knot may fall out. The presence of knots reduces the mechanical properties of the cross-section and can represent a sensitive area. The grain direction is rarely aligned with the axis of a wood tree/piece and when summed to drying twists leads to the loss of uniformity of sawed wood. If a tree grows submitted to wind/snow or in pitched areas, it usually grows unevenly. When this happens, growth rings are more spaced in one side than in the other, resulting in reaction wood and tension wood. Density is related to the rate of growth which is a function of the growth conditions (e.g. quantity of water during growth) (Ramage *et al.*, 2017a). Resin pockets are compartments extending parallel to the annual rings, usually to the inner side and filled with resin. The influence of resin pockets on mechanical properties depends on their size and number.

Wane is a reduction of the cross-section that shall be taken into account in order to avoid stress concentration. Warp in wood usually results from fast drying processes or bad packaging procedures. Although it does not compromise the mechanical properties, a warp may hamper the constructive process. Fissures can be originated by growing stresses, the presence of knots or of reaction wood, or by the drying process. They lead to a discontinuity in timber and can represent a high influence on its strength properties (Cachim, 2014).

Figure 8 - a) Reaction wood; b) Knots and resin pockets; c) Cracks

3.2.2 Physical properties

Cachim (2014) refers that the main factors that influence the physical properties of wood are: water (moisture content) and the relation between water and wood (hygroscopicity) and the differences of the properties in different directions of the trunk (anisotropy).

Wood is a hygroscopicity material with exchanges of water with the exterior until moisture balance is reached. The water content in wood is measured by the moisture content and quantified using Equation 2.

$$MC\ (\%) = \frac{m_{water}}{m_{dry\_wood}} \times 100 = \frac{m_{wet} - m_{dry\_wood}}{m_{dry\_wood}} \times 100 \qquad (2)$$

Where: MC is the moisture content; m_{water} is the mass of water; m_{dry_wood} is the mass of dry wood; and m_{wet} is the mass of wood with the actual moisture content.

Green wood (after being cut), when exposed to air, loses some water (free water). When all the free water (water that is contained in the cell cavities and intercellular spaces of wood) is expelled, the wood fibres reach the fibre saturation point. The fibre saturation point of wood varies from species to species, usually between 25% and 35% (FPL, 2010). Under the fibre saturation point, the remaining water is stored in the cell walls of wood (bound water). To reduce the moisture content of wood until 12%, average equilibrium value for most softwoods for indoor conditions (20ºC and 65% air humidity), usually assumed as the reference equilibrium moisture content for construction applications, it is necessary to use exterior energy, since water is chemically bound.

The variation of moisture content below the fibres saturation point leads to dimensional variations of wood (shrinkage for losses of bound water and expansion for increases of bound water) (Cachim, 2014). For each combination of temperature and relative humidity, there is a point of equilibrium between the internal diffusion of water and movement of this water to the exterior, called the equilibrium moisture content. When timber is dried, the main objective is to bring the moisture content to the expected equilibrium value in the actual application conditions during its service life.

The volumetric shrinkage of wood depends on the species and the direction relative to the trunk. Wood shrinkage is expressed in terms of the percentage of dimensional variations (usually considering radial, tangential, axial and volumetric). As wood presents different properties for different directions (anisotropic material), during the drying process the dimensions of wood vary in each direction and, consequently, wood warps can appear.

Density is the ratio between mass and volume and is usually expressed in kg/m^3. It is one of the main characteristics of wood since most of its mechanical properties are determined based on it. Density may vary according to the moisture content and is usually referred to 12% moisture content. For structural applications, three types of density are defined: mean values (for serviceability limit states design) and characteristic values: superior (for load determinations), and inferior (for ultimate limit states design).

3.2.3 Mechanical properties

The mechanical properties of wood are obtained based on the grade of structural timber. Structural grade or class of timber (shown in Table 12 and Table 13) results from the classification of timber based on particular values of mechanical properties and density. Figure 9 shows the European Standards procedure to determine the structural class of wood. EN 14081-1 (CEN, 2016a) proposes two parallel systems for grading: visual and mechanical. Both systems relate measures made by non-destructively methods in a wood piece with properties determined previously by destructive methods.

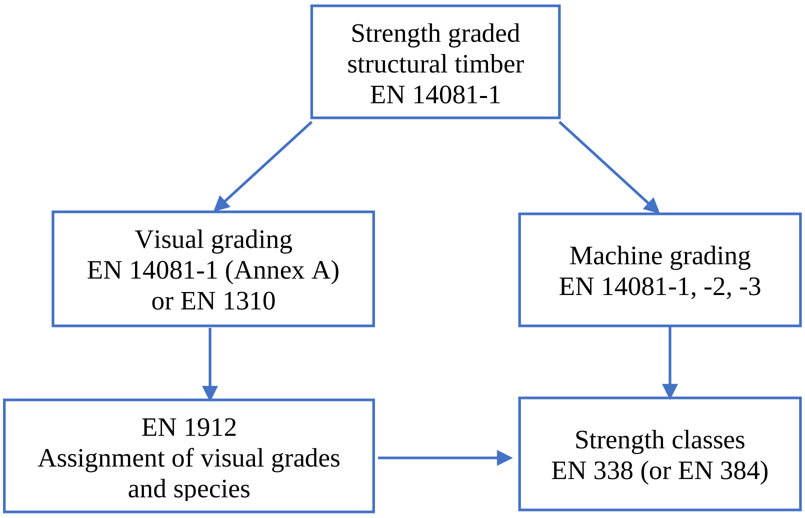

Figure 9 - Process for structural grading of timber

3.2.3.1 **Visual grading**

Visual strength grading is the process by which timber is sorted by visual inspection and assessment into a grade to which characteristic values of strength, stiffness and density may be allocated, based on EN 1912 (CEN, 2012b). The visual inspection identifies and quantifies the features that affect strength, stiffness and density of wood elements, such as knots, slope of grain, ring width and presence of reaction wood. The standards specify limits for those features and assign the wood pieces to a given grade. The grades are allocated to strength classes based on the results of destructive tests performed previously for specific wood species and growth area.

3.2.3.2 **Mechanical grading**

Machine strength grading is a process by which a piece of timber can be sorted by a non-destructively machine test on one or more properties of the timber for which values of strength, stiffness and density may be allocated. The assignment of the determined properties to a strength class is based on a rejection criterion in which the values of determined properties are allocated into one, two or three strength classes. Output control of machine grading requires an adjustment of machine settings based on tests performed periodically to wood samples. Grading machine settings are unique for each combination of wood species and growth area. The machine grading process shall be done according to EN 14081-1 (CEN, 2016a), EN 14081-2 (CEN, 2018a), and EN 14081-3 (CEN, 2018b).

The mechanical grading attributes a strength class to a wood piece by quantifying the indicating properties. The attribution of a strength class to a wood piece is based on mechanical tests performed previously for each combination of wood species and country of origin. The mechanical tests quantify bending or tension properties of wood elements. After performing the tests, a statistical procedure defines one or more combinations of one, two or three strength classes for which each combination of wood species and country of origin is suitable to be classified. In some studies and reports, for each combination of strength classes, the percentage of wood elements that belong to each strength class is given.

3.3 **Wood species**

Different wood species usually have different properties. According to the study’s scope, five wood species are analysed: Norway spruce (*Picea Abies* H. Karst.); Scots pine (*Pinus Sylvestris* L.); Maritime pine (*Pinus Pinaster* Aiton); Cryptomeria (*Cryptomeria Japonica* D. Don); and Eucalyptus (*Eucalyptus globulus* Labill.).

3.3.1 Norway spruce (Picea Abies)

Norway spruce is a large coniferous tree (softwood) and one of the most important species in Europe for its economic and ecological aspects (Caudullo *et al.*, 2016). The trees can grow up to 50-60 m and diameters can reach 150 cm (Figure 10-a). This species can be found from the mountains of Central Europe to Northern and Eastern Europe (Figure 10-b). In the northern European countries, the Norway spruce solid wood is used for construction and for paper production. The wood is also used as joinery timber, furniture, veneer and as tone-wood (used as a material for musical instruments).

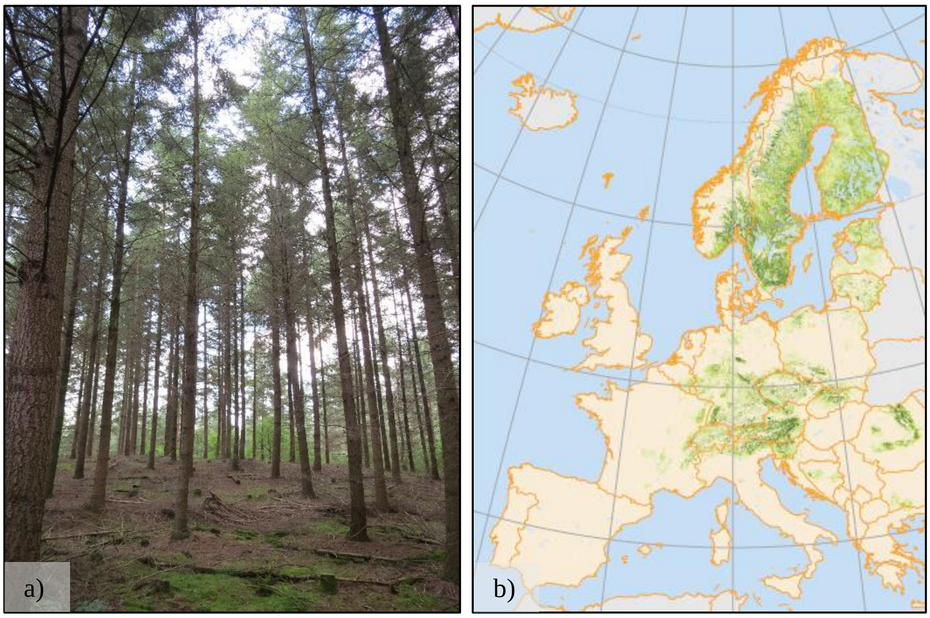

Figure 10 - a) Norway spruce forest (Copyright AnRo0002, commons.wikimedia.org); b) distribution map of Norway spruce (Caudullo *et al.*, 2016)

According to EN 1912 (CEN, 2012b), the Norway spruce visual grading strength classes can vary from C14 to C30. The strength classes, country of origin, and grading rule publishing country of Norway spruce are presented in Table 3.

For this study the Norway spruce wood is considered to be grown and sawn in Germany and Sweden. Ranta-Maunus *et al.* (2011) quantified and summarized the bending strength, modulus of elasticity and density of Norway spruce sawn in Sweden and Germany. These properties were determined through destructive tests, and theirs mean values are shown in Table 4.

Table 3 - Strength classes, country of origin and publishing country of Norway spruce sawnwood

Strength Class	Publishing Country	Country of Origin
C30	France	France
	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North-eastern Europe
	Germany, Austria and Czech Republic	Central, North and Eastern Europe
	Slovak Republic	Slovak Republic
C24	France	France
	Germany, Austria and Czech Republic	Central, North and Eastern Europe
	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North-eastern Europe
	United Kingdom	Central, North and Eastern Europe
	Slovak Republic	Slovak Republic
C18	France	France
	Germany, Austria and Czech Republic	Central, North and Eastern Europe
	Ireland	Ireland
	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North-eastern Europe
	United Kingdom	United Kingdom
C16	United Kingdom	Central, North and Eastern Europe
	Slovak Republic	Slovak Republic
C14	United Kingdom	United Kingdom
	Ireland	Ireland
	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North Eastern Europe

Table 4 – Mean values of bending strength, modulus of elasticity and density of Norway spruce sawnwood

	Bending strength	Modulus of elasticity	Density (12% of MC)	Number of specimens
Units	N/mm^2	N/mm^2	kg/m^3	p
Sweden	44.8	12300	435	4393
Germany	41.5	12100	441	3538

3.3.2 Scots pine (Pinus Sylvestris)

According to Durrant *et al.* (2016), Scots pine is a medium-sized conifer tree (softwood) that usually reaches between 23 and 27 m in height. In Figure 11-a, an example of a Scots pine forest is presented. In Europe, it occupies a range from southern Spain to northern Scandinavia (Figure 11-b). The Scots pine wood is easily workable and is one of the softwoods with higher strength and stiffness properties which makes it quite suitable as construction timber as well as for furniture.

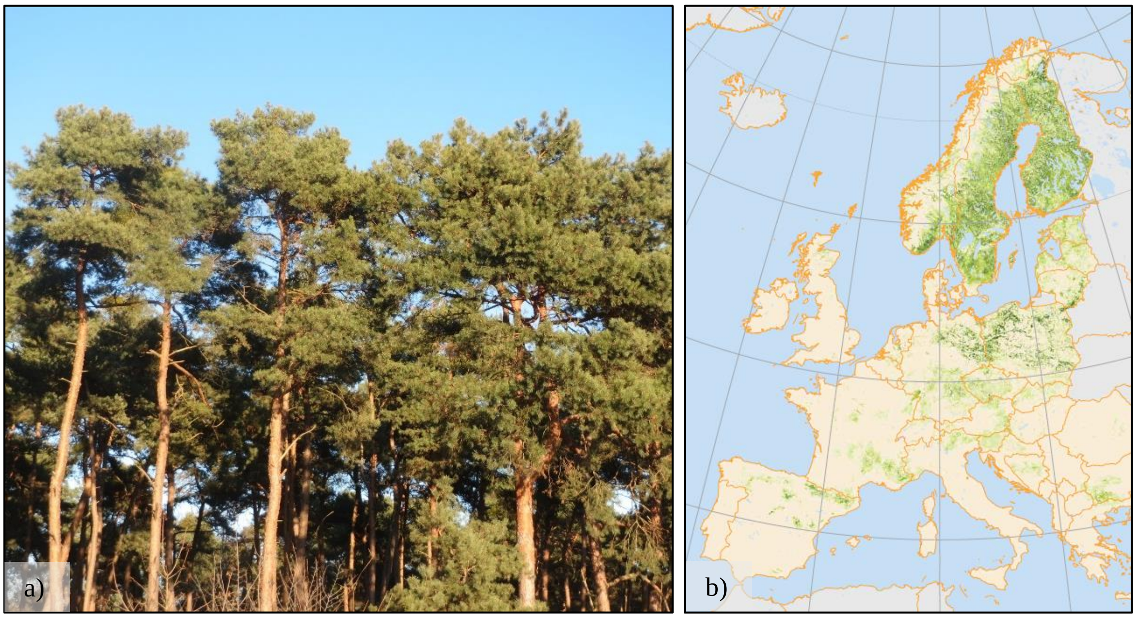

Figure 11 – a) Scots pine forest (Copyright AnRo0002, commons.wikimedia.org); b) distribution map of Scots pine (Durrant *et al.*, 2016)

The EN 1912 (CEN, 2012b) assign the Scots pine structural classes between C14 and C30. The strength classes, country of origin, and grading rule publishing country of Scots pine are presented in Table 5.

Table 5 – Strength classes, country of origin and publishing country of Scots pine sawnwood

Strength Class	**Publishing country**	**Country of Origin**
C30	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North-eastern Europe
	Germany, Austria and Czech Republic	Central, North and Eastern Europe
C27	Spain	Spain
C24	France	France
	Germany, Austria and Czech Republic	Central, North and Eastern Europe
	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North-eastern Europe
	United Kingdom	Central, North and Eastern Europe
C22	United Kingdom	United Kingdom
	Spain	Spain
C18	France	France
	Germany and Austria	Central, North and Eastern Europe
	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North-eastern Europe
	Spain	Spain
C16	United Kingdom	Central, North and Eastern Europe
C14	United Kingdom	United Kingdom
	Denmark, Finland, Iceland, Norway, and Sweden.	Northern and North-eastern Europe

Pinus Sylvestris wood is considered to be grown and sawn in Germany and Sweden. Ranta-Maunus *et al.* (2011) quantified and summarized the bending moment, modulus of elasticity and density of Pinus Sylvestris sawn in Sweden and Germany. Table 6 shows the mean values of these properties that were determined through destructive tests.

Table 6 – Mean values of bending strength, modulus of elasticity and density of Scots pine sawnwood

	Bending moment	**Modulus of elasticity**	**Density (12% of MC)**	**Number of specimens**
Units	N/mm^2	N/mm^2	kg/m^3	p
Sweden	44.7	11300	481	209
Germany	38.6	11900	493	421

3.3.3 Maritime pine (Pinus Pinaster)

Maritime pine is a medium-size softwood tree (Figure 12-a) native to the western Mediterranean basin. The tree reaches between 20-30 m of height (Viñas *et al.*, 2016). In Europe, the Maritime pine occupies the Iberian Peninsula, the South and West of France, the West of Italy and Western Mediterranean isles (Figure 12-b). In Portugal, the Maritime pine was widely used for boatbuilding during the 15th century and as construction product, and it also has been used during the last centuries for dune stabilisation and to prevent the erosion of the coast (Viñas *et al.*, 2016). The wood of Maritime pine can be used as construction material, furniture, poles and posts.

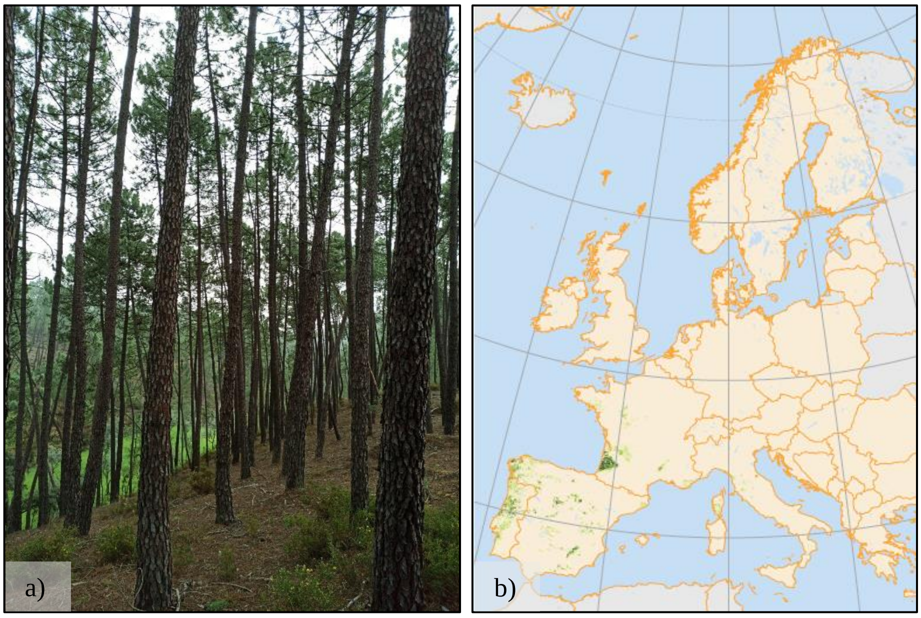

Figure 12 – a) Maritime pine forest; b) distribution map of Maritime pine (Viñas *et al.*, 2016)

According to EN 1912, the range of Maritime pine structural classes is between C18 and C24. Machado *et al.* (2011) identify the possibility of also considering Maritime pine wood as C30. The structural classes identified by LNEC (1997), Machado *et al.* (2011) and EN 1912 (CEN, 2012b) are presented in Table 7.

Table 7 – Strength classes, country of origin and publishing country of Maritime pine sawnwood

Strength Class	Publishing country	Country of Origin
C30	Portugal	Portugal
C24	Spain	Spain
	France	France
	Portugal	Portugal
C18	Spain	Spain
	France	France
	Portugal	Portugal
	Spain	Spain

DEC-UC & SerQ (2014) graded 866 wood pieces into three combinations of strength classes. The mean values of bending moment, modulus of elasticity and density of this sample are shown in Table 8. The strength classes considered in the assessment and their yield are shown in Table 9.

Table 8 – Mean values of bending strength, modulus of elasticity and density of Maritime pine sawnwood

	Bending moment	Modulus of elasticity	Density (12% of MC)	Number of specimens
Units	N/mm^2	N/mm^2	kg/m^3	p
Portugal	54.1	12900	597	866

Table 9 – Mechanical grading combinations, strength classes and yield of Maritime pine sawnwood

Combination	Strength classes	Yield [%]
C40/C24/C18/Rejected	C40	74.0
	C24	14.9
	C18	5.6
	Rejected	5.5
C35/C24/C18/Rejected	C35	81.9
	C24	6.9
	C18	6.6
	Rejected	4.6
C24/Rejected	C24	97.6
	Rejected	2.4

3.3.4 Cryptomeria (Cryptomeria Japonica)

Cryptomeria is the most significant softwood specie in the Azores archipelago, in Portugal (approximately 13000 ha) and its applicability in construction is under study. The Cryptomeria can be used for construction, insulation, and furniture. This tree can reach 50 m in height (Figure 13). SerQ (2019) identifies one main structural class for Cryptomeria: C14.

Figure 13 – Cryptomeria forest (Copyright Lombroso, commons.wikimedia.org

SerQ (2019) quantified the bending strength, modulus of elasticity and density of 511 wood pieces of Cryptomeria from Azores. The results are shown in Table 10.

Table 10 – Mean values of bending strength, modulus of elasticity and density of Cryptomeria sawnwood

	Bending strength	**Modulus of elasticity**	**Density (12% of MC)**	**Number of specimens**
Units	N/mm^2	N/mm^2	kg/m^3	p
Portugal (Azores)	26.0	6189	309	511

3.3.5 Eucalyptus (Eucalyptus globulus).

The Eucalyptus globulus is a hardwood tree native to the south-eastern Australia, introduced in south-western Europe in the middle of the19th century, mainly for industrial purposes (i.e. timber and paper pulp) (Cerasoli *et al.*, 2016). A Eucalyptus tree can reach approximately 70 m of height (Figure 14-a). In Europe, Eucalyptus can be mainly found in the Iberian Peninsula, as well as in France and Italy (Figure 14-b).

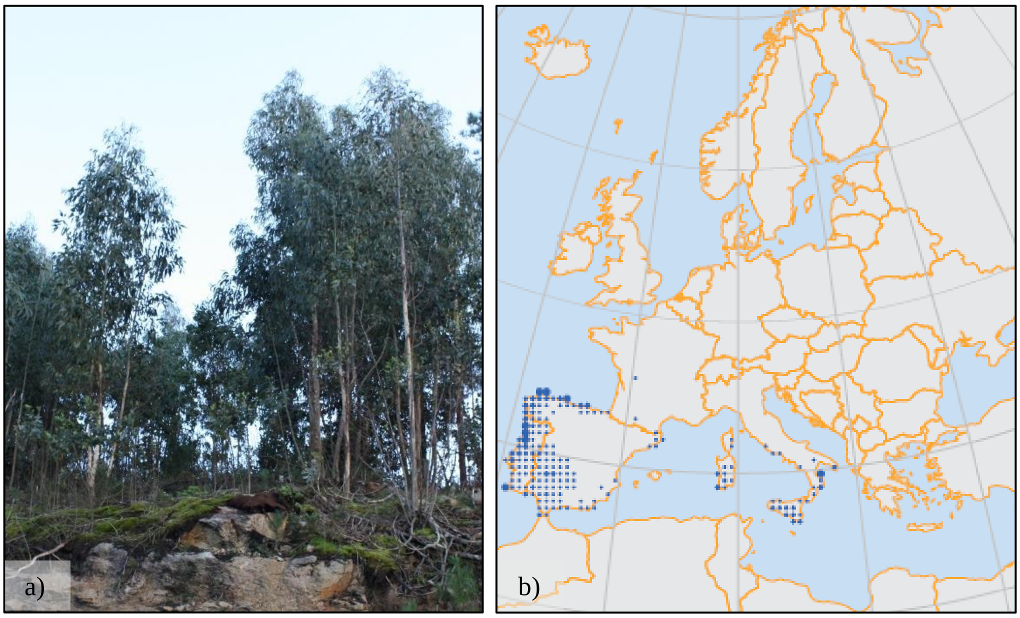

Figure 14 – a) Eucalyptus Forest (Copyright Lombroso, commons.wikimedia.org); b) distribution map of Eucalyptus (Cerasoli *et al.*, 2016)

The use of this wood in construction needs some care during the sawing and drying process to minimize defects. According to EN 1912 (2012b), the Eucalyptus is classified as a D40 class with origin in Spain. Martins (2015) conducted a mechanical characterization of Eucalyptus from Portugal and quantified the bending strength, modulus of elasticity and density of 130 wood pieces. The mean values of those properties are shown in Table 11. The authors indicated that the analysed sample could be graded as D40.

Table 11 – Mean values of bending strength, modulus of elasticity and density of Eucalyptus sawnwood

	Bending strength	**Modulus of elasticity**	**Density (12% of MC)**	**Number of specimens**
Units	N/mm^2	N/mm^2	kg/m^3	p
Portugal	75.9	18151	905.3	130

3.4 Structural timber products and structural design

3.4.1 Structural timber products

There is a large number of wood-based products with application in construction. For a long time, the structural application of timber was limited to the length of the logs. The industrialization in the timber industry during the 20th century led to the development of reconstituted sections with larger dimensions. In this work, the following structural products, which are described next, were considered: sawnwood (SW); glued laminated timber (GLT), LVL and I-joist beams. The structural solutions designed in this study consider the use of orientated strand boards (OSB) in residential floors.

3.4.1.1 **Solid timber (or sawnwood) (SW)**

SW, apart from roundwood, this is the most rudimentary structural wood product (Figure 15). The most common fabrication process starts with cutting roundwood logs, followed by debarking, crosscutting, sawing, drying, planing and grading (and, if required, finger jointing) (Moore & Cown, 2015). The performance requirements of structural solid timber are defined in EN 14081-1 (CEN, 2016a).

The main disadvantages of structural solid timber are the limitation of dimensions (tree size and machinery limitations) and the high variability of properties (due to defects). The main advantage of solid timber is the less energy and equipment required during manufacturing.

In this study, the design was made considering softwood and hardwood species, defined at section 3.3 and available in the national and European construction market. The strength, stiffness and density properties of structural classes for softwood and hardwood solid timber defined by EN 338 (CEN, 2009b) are shown in Table 12 and Table 13, respectively.

Table 12 – Strength, stiffness and density properties of softwood SW strength classes

Property	Symbol	Unit	C18	C24	C30	C35	C40
Bending	$f_{m,k}$	N/mm^2	18	24	30	35	40
Tension ||	$f_{t,0,k}$	N/mm^2	11	14	18	21	24
Tension |-	$f_{t,90,k}$	N/mm^2	0.4	0.4	0.4	0.4	0.4
Compression ||	$f_{c,0,k}$	N/mm^2	18	21	23	25	26
Compression |-	$f_{c,90,k}$	N/mm^2	2.2	2.5	2.7	2.8	2.9
Shear	$f_{v,k}$	N/mm^2	3.4	4	4	4	4
Mean modulus of elasticity ||	$E_{0,mean}$	kN/mm^2	9	11	12	13	14
5% Modulus of elasticity ||	$E_{0,05}$	kN/mm^2	6	7.4	8	8.7	9.4
Mean modulus of elasticity |-	$E_{90,mean}$	kN/mm^2	0.3	0.37	0.4	0.43	0.47
Mean shear modulus	G_{mean}	kN/mm^2	0.56	0.69	0.75	0.81	0.88
Characteristic density	ρ_k	kg/m^3	320	350	380	400	420
Mean density	ρ_{mean}	kg/m^3	380	420	460	480	500

Table 13 – Strength, stiffness and density properties of hardwood SW strength classes

Property	Symbol	Unit	D24	D30	D35	D40
Bending	$f_{m,k}$	N/mm^2	24	30	35	40
Tension ||	$f_{t,0,k}$	N/mm^2	14	18	21	24
Tension |-	$f_{t,90,k}$	N/mm^2	0.6	0.6	0.6	0.6
Compression ||	$f_{c,0,k}$	N/mm^2	21	23	25	26
Compression |-	$f_{c,90,k}$	N/mm^2	7.8	8	8.1	8.3
Shear	$f_{v,k}$	N/mm^2	4	4	4	4
Mean modulus of elasticity ||	$E_{0,mean}$	kN/mm^2	10	11	12	13
5% modulus of elasticity ||	$E_{0,05}$	kN/mm^2	8.5	9.2	10.1	10.9
Mean modulus of elasticity |-	$E_{90,mean}$	kN/mm^2	0.67	0.73	0.8	0.86
Mean shear modulus	G_{mean}	kN/mm^2	0.62	0.69	0.75	0.81
Characteristic density	ρ_k	kg/m^3	485	530	540	550
Mean density	ρ_{mean}	kg/m^3	580	640	650	660

Figure 15 – Solid timber (dataholz.eu)

3.4.1.2 Glued laminated timber (GLT)

GLT (or glulam) is composed of two or more parallel graded and selected laminations (from 6 mm to 45 mm) connected with a structural glue (Figure 16). The typical production of glulam begins with the arrival of green sawnwood, followed by the drying of lamellas, strength grading, finger jointing, planing, gluing, pressing and curing, and finishing. The glulam performance requirements, minimum production requirements and evaluation of conformity are established in EN 14080 (CEN, 2013a).

The main advantages of glulam are the high range of dimensions that are possible in production and the reduction of wood defects. The main disadvantages are the energy required for fabrication and the presence of chemical products in the glues which might be harmful to health. EN 14080 (CEN, 2013a) defines two types of glues: I and II. Type I resins can be used in service classes 1, 2 and 3 (defined in section 3.4.2). Type II can only be applied in service class 1.

There are two types of glulam: homogeneous (lamellas with the same structural grade) and combined (lamellas with a different structural grade). In the National and European market of timber structures, materials from both types of glulam can be found; however, the homogeneous glulam is the most common. This study considers three strength classes of glulam. The characteristic strength and stiffness properties of GLT of each strength class given by EN 14080 (CEN, 2013a) are presented in Table 14.

Table 14 – Strength, stiffness and density properties of GLT strength classes

Property	Symbol	Unit	GL 24 h	GL 28 h	GL 32 h
Bending	$f_{m,k}$	N/mm^2	24	28	32
Tension ||	$f_{t,0,k}$	N/mm^2	19.2	22.3	25.6
Tension |-	$f_{t,90,k}$	N/mm^2	0.5	0.5	0.5
Compression ||	$f_{c,0,k}$	N/mm^2	24	28	32
Compression |-	$f_{c,90,k}$	N/mm^2	2.5	2.5	2.5
Shear	$f_{v,k}$	N/mm^2	3.5	3.5	3.5
Mean modulus of elasticity ||	$E_{0,mean}$	kN/mm^2	11.5	12.6	14.2
5% modulus of elasticity ||	$E_{0,05}$	kN/mm^2	9.6	10.5	11.8
Mean modulus of elasticity |-	$E_{90,mean}$	kN/mm^2	0.3	0.3	0.3
Mean shear modulus	G_{mean}	kN/mm^2	0.65	0.65	0.65
Characteristic density	ρ_k	kg/m^3	385	425	440
Mean density	ρ_{mean}	kg/m^3	420	460	490

Figure 16 – Glued laminated timber (dataholz.eu)

3.4.1.3 **Laminated Veneer Lumber (LVL)**

LVL results from the bonding of rotary peeled or sliced thin wood veneers (maximum of 6 mm per veneer) under heat and pressure (Figure 17). Manufacturing of LVL starts with the debarking of logs, followed by tops cutting, peeling, drying (oven); classification of lamellas, gluing, pressure under heat; trimming and grading. The requirements for the structural use of LVL are given by EN 14374 (CEN, 2004), namely tests to be used and the evaluation of conformity methods.

The main advantages of LVL are the high possible range of dimensions and high strength properties (low variability and randomised wood properties). Excessive costs and the influence of adhesive quality on product quality are singled out as the main disadvantages of LVL.

EN 14374 (CEN, 2004) does not establish strength classes for LVL and refers that properties shall be determined based on standardized tests. In this study, the LVL available in the European market is used, considering one of the production companies identified by Portuguese construction companies. The product considered in this study was KertoS®, whose strength and stiffness properties are presented in Table 15.

Table 15 – Strength, stiffness and density properties of KertoS®

Property	Symbol	Unit	LVL
Bending	$f_{m,k}$	N/mm^2	44
Tension ||	$f_{t,0,k}$	N/mm^2	35
Tension |-	$f_{t,90,k}$	N/mm^2	0.8
Compression ||	$f_{c,0,k}$	N/mm^2	35
Compression |-	$f_{c,90,k}$	N/mm^2	6
Shear	$f_{v,k}$	N/mm^2	4.1
Mean modulus of elasticity ||	$E_{0,mean}$	kN/mm^2	13.8
5% modulus of elasticity ||	$E_{0,05}$	kN/mm^2	11.6
Mean modulus of elasticity |-	$E_{90,mean}$	kN/mm^2	-
Mean shear modulus	G_{mean}	kN/mm^2	0.6
Characteristic density	ρ_k	kg/m^3	480
Mean density	ρ_{mean}	kg/m^3	510

Figure 17 – Laminated Veneer Lumber (dataholz.eu)

3.4.1.4 **Orientated strand boards (OSB)**

OSB are produced by compressing layers of wood strands in specific orientations combined with adhesives (Figure 18). According to EN 300 (CEN, 2006), there are four types of OSB: OSB/1 – non-load-bearing panels and panels for interior use in dry conditions; OSB/2 – load-bearing panels for use in dry conditions; OSB/3 – load-bearing panels for use in humid conditions; and OSB/4 – heavy-duty load-bearing panels for use in humid conditions. This study considers the OSB/3 type of product for which strength and stiffness properties for products with a thickness higher than 25 mm are given in Table 16.

The main advantages of OSB are the availability of many sizes and the versatility (large number of structural and non-structural applications). The main disadvantage of OSB is the low resistance to humidity and water exposure.

Table 16 – Strength, stiffness and density properties of OSB/3

	Symbol	**Units**	**OSB/3**
Bending	$f_{m,k}$	N/mm^2	14.8
Bending |-	$f_{m,90,k}$	N/mm^2	7.4
Tension ||	$f_{t,0,k}$	N/mm^2	9
Tension |-	$f_{t,90,k}$	N/mm^2	6.8
Compression ||	$f_{c,0,k}$	N/mm^2	14.8
Compression |-	$f_{c,90,k}$	N/mm^2	12.4
Shear	$f_{v,k}$	N/mm^2	6.8
Shear plane	$f_{r,k}$	N/mm^2	1
Mean modulus of elasticity ||	$E_{0,mean}$	kN/mm^2	4.93
Mean modulus of elasticity |-	$E_{90,mean}$	kN/mm^2	1.98
Mean modulus of elasticity ||	$E_{0,t,mean}$	kN/mm^2	3.8
Mean modulus of elasticity |-	$E_{90,t,mean}$	kN/mm^2	3
Mean modulus of elasticity compression ||	$E_{0,c,mean}$	kN/mm^2	3.8
Mean modulus of elasticity compression |-	$E_{90,tc,mean}$	kN/mm^2	3
Mean shear modulus |-	$G_{mean,per}$	kN/mm^2	1.08
Mean shear modulus ||	$G_{mean,r}$	kN/mm^2	0.05
Characteristic density	ρ_k	kg/m^3	550

Figure 18- OSB panels (dataholz.eu)

3.4.1.5 **I-Joist beams (IJ)**

IJ beams have an I-shaped cross-section, composed of Oriented Strand Board (OSB) or Hard Boards (HB) in the web and LVL or solid timber in the flanges (Figure 19). OSB manufacturing starts with log sorting, followed by debarking, stranding, drying, blending, forming line, and pressing. The beginning of I-joist production can be divided into two sub-processes: the preparation of flanges and the preparation of webs. The preparation of webs starts with cutting off the OSB boards, followed by the preparation of panels for the joists. The preparation of flanges starts with cutting off the panels and is followed by notching the flanges. I-joist manufacturing finishes with the connection of the webs and flanges using glue, followed by cutting and drying.

As a main advantage, I-joists are light structures when compared to equivalent structural solutions, while the number of chemical products used in fabrication and the complexity of connections between elements are pointed out as their main disadvantages.

In this study, the design is made considering two types of I-Joists, varying the flanges' material: LVL and SW. The web of both is made of OSB/3. The SW and LVL materials assumed in this study were C24 and LVL properties given in Section 3.4.1.1 and 3.4.1.3, respectively. The design of these products follows the procedures given by Swedish Wood (2016b).

Figure 19 – I-joist beams (dataholz.eu)

3.4.2 Structural design

According to EN 1995-1-1 (CEN, 2014c), structural design shall consider: different material properties; different behaviour of materials over time; different climatic conditions; and different design conditions.

The design methodology for timber structures follows three main steps: quantification of actions and stresses, quantification of strength properties, and ULS and SLS verifications.

The quantification of actions and stresses can be divided into three steps: quantification of actions; combination of actions; and use of structural calculation models. These steps are schematized in Figure 20.

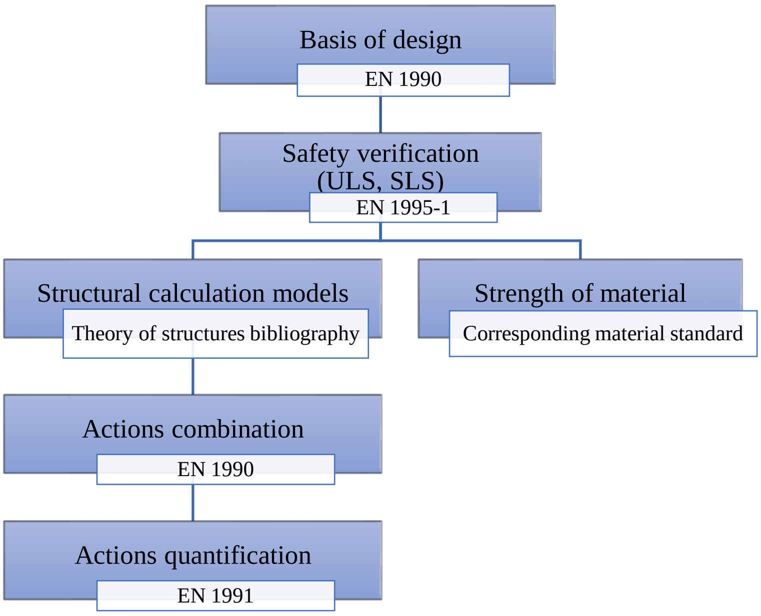

Figure 20 – Structural timber design methodology

3.4.2.1 **Loads and load combinations**

EN 1990 (CEN, 2011b) gives information to classify and combine the different loads applied on the structure, considering their different origins, duration and nature. Based on EN 1991-1-1 (CEN, 2011c), actions shall be classed as direct (e.g. permanent, variable, wind, snow and earthquake) or indirect (e.g. support displacement and moisture content variation).

The load duration and moisture content during the service life of a structure affect the strength and stiffness of the wood elements. EN 1995-1-1 (CEN, 2014c) defines classes for load duration and climatic conditions for timber design (service class).

The duration of loads affects the strength properties of wood-based materials. For design purposes, EN 1995-1-1 (CEN, 2014c) divides load actions in classes (based on their duration). These classes can be observed in Table 17.

The environmental conditions can affect the deformation and strength values of timber. In order to classify them, EN 1995-1-1 (CEN, 2014c) defines three service classes (SC):

- SC 1: moisture content corresponding to a temperature of 20 ºC and a relative humidity lower than 65%, or higher only a few weeks per year,

- SC 2: moisture content corresponding to a temperature of 20 ºC and a relative humidity lower than 85%, or higher only a few weeks per year,
- SC 3: climatic conditions that lead to higher moisture contents.

Table 17 – Load duration classes from EN 1995-1-1

Load duration class	Duration of characteristic load
Permanent	More than 10 years
Long-term	Between 6 months and 10 years
Medium-term	Between 1 week and 6 months
Short-term	Less than one week
Instantaneous	(e.g. accidental load)

EN 1990 (CEN, 2011b) gives a set of combinations that combines the values of actions that are considered to occur simultaneously. The combinations of actions intend to determine the design values of the effects of actions for the verification of safety requirements (Ultimate Limit States (ULS)) and serviceability requirements (Service Limit States (SLS)). The combinations shall be calculated according to procedures given in Chapter 6 of EN 1990 (CEN, 2011b): fundamental, accidental and seismic for ULS; and characteristic, frequent, and quasi-permanent actions for SLS.

3.4.2.2 **Structural analysis**

The structural analysis shall be done using appropriate design models. A linear-elastic behaviour shall be considered in structural analysis, except for cases where plastic behaviour can be considered. In such cases, the plastic deformation capacity of the systems shall be verified. (EN 1995-1-1 (CEN, 2014c))

3.4.2.3 **Material properties**

Wood-based materials present a high variability of mechanical properties in comparison with other common building materials such as steel and concrete. The mechanical properties of a material can be determined in three ways:

i) Tests with different loads applied on the structure,
ii) Comparison with similar species of wood or wood-based materials' grades,
iii) Based on established relations between different properties of the material.

The design resistance of materials, Rd, shall be calculated by Equation 2.

$$R_d = k_{sys} k_h k_{mod} \frac{R_k}{\gamma_M} \tag{2}$$

The characteristic value of load-carrying capacity, R_k, represents the characteristic resistance values of each material and can be consulted in specific standards for each material. The partial factor for material properties, γ_M, depends on the material and ULS combination used. The recommended values are presented in Table 18.

Table 18 – Recommended values for γ_M, based on EN 1995-1-1

Combination	**Material**	γ_M
Fundamental	SW	1.3
	GLT	1.25
	LVL, plywood, OSB	1.2
	Connections	1.3
	Punched metal plate fasteners	1.25
Accidental	-	1.0

The modification factor, k_{mod}, considers the effect of load duration and moisture content in structural design. The table that combines the values for each material according to the duration class and service class can be found in EN 1995-1-1 (CEN, 2014c) (Table 19). When solid timber, glulam or LVL are used, EN 1995-1-1 (CEN, 2014c) refers that the effect of member size shall also be considered in the analysis, considering factor k_h presented in Table 20.

Table 19 – Values for k_{mod}, based on EN 1995-1-1

Material	**Service class**	**Duration classes**				
		Permanent action	Long term action	Medium term action	Short term action	Instantaneous action
SW **GLT** **LVL**	1	0.60	0.70	0.80	0.90	1.10
	2	0.60	0.70	0.80	0.90	1.10
	3	0.50	0.55	0.65	0.70	0.90

The system strength factor, k_{sys}, considers the possibility of a load supported by one member to be distributed to similar neighbouring elements (e.g. floors). The use of this factor requires that several parallel elements, equally spaced, are interconnected by transversal elements that allow load distribution. The strength verification requires that loads' duration should be assumed as short-term. $k_{s's}$ shall be considered equal to 1.1. For laminated timber floors or decks, this value varies with the number of loaded beams and the type of connections between layers. This variation can be consulted in section 6.6 (4) of EN 1995-1-1 (CEN, 2014c). When the timber application does not comply with these design requirements, k_{sys} shall be considered equal to 1.

Table 20 – Situations for k_h value

Material	Dimension	Affected values	$\boldsymbol{k_h}$
SW $\boldsymbol{\rho_k \leq 700\ \frac{kg}{m^3}}$	Bending – depth < 150 mm Tension – width < 150 mm	$f_{m,k}$ $f_{t,0,k}$	$min\begin{cases}\left(\frac{150}{h}\right)^{0.2}\\ 1.3\end{cases}$
GLT	Bending – depth < 600 mm Tension – width < 600 mm	$f_{m,k}$ $f_{t,0,k}$	$min\begin{cases}\left(\frac{600}{h}\right)^{0.1}\\ 1.1\end{cases}$
LVL	Bending – depth ≠ 3000 mm	$f_{m,k}$	$min\begin{cases}\left(\frac{300}{h}\right)^{s*}\\ 1.2\end{cases}$
	Tension – length ≠ 3000 mm	$f_{t,0,k}$	$min\begin{cases}\left(\frac{3000}{l}\right)^{s*/2}\\ 1.1\end{cases}$
	s* - size effect exponent shall be taken in accordance with EN 14374		

The stiffness of materials (E_d or G_d) for design shall be calculated using equations 3 and 4.

$$E_d = \frac{E_{mean}}{\gamma_M} \tag{3}$$

$$G_d = \frac{G_{mean}}{\gamma_M} \tag{4}$$

Where: E_{mean} is the mean value of the modulus of elasticity; and G_{mean} is the mean value of the shear modulus.

In this study, the design of sawnwood, glulam and LVL elements consider the ULS and SLS design limitations imposed by Chapters 6 and 7 of EN 1995-1-1 (CEN, 2014c). In the ULS design of floors, the stresses are verified in: compression perpendicular to the grain (6.1.5 of EN 1995-1-1 (CEN, 2014c)); bending (6.1.6 of EN 1995-1-1 (CEN, 2014c)) and shear (6.1.7 of EN 1995-1-1 (CEN, 2014c)). Finally, the stability of members is also verified (6.3 of EN 1995-1-1 (CEN, 2014c)). The SLS verification is made for the limiting values for the deflection of beams (7.2 of EN 1995-1-1 (CEN, 2014c)).

The design of I-Joist elements is made by verifying the limitations imposed by Chapter 9 of EN 1995-1-1 (CEN, 2014c) and considered the formulation proposed by Swedish Wood design guides (Swedish Wood, 2016a, 2016b). The tension in the middle of the flange, the tension in the edge of the flange, the stress in the web, and the shear in element are verified. The constructive solution considers that elements are braced sideways so that lateral buckling cannot occur. The SLS limits verification follows the formulation proposed by Swedish wood (2016b) to determine if the elements' deflection accord with EN 1995-1-1 (CEN, 2014c).

3.5 **Durability**

The durability of wood is defined in EN 1001-2 (CEN, 2005) as the resistance of this material to destruction by its degrading agents (atmospheric and biologic), i.e. the capability of wood products to accomplish the design requirements without unexpected maintenance or rehabilitation. Atmospheric agents include heat, oxygen, moisture, chemical products resulting from pollution and sunlight; biological agents include fungi, insects (beetles and termites) and marine borers. The biological agents do cause a significantly higher impact on the integrity of wood elements than atmospheric agents and, for that reason, regarding structural performance, only the biological agents are assessed by durability standards. Such agents are identified in EN 335 (CEN, 2013b): wood-destroying fungi (*basidiomycete wood-rotting fungi* and *soft-rot fungi*), *Coleoptera* (beetles – *Anobium punctatum* and *Hylotrupes bajulus*), *Isoptera* (termites) and marine borers. Whenever the occurrence of a biological attack is expected during the service life of wood elements, a durability design shall be made.

3.5.1 Durability design

According to EN 335 (CEN, 2013b), the durability design of wood products should follow the flowchart presented in Figure 21 (adapted from EN 351-1 (CEN, 2007)).

The first step of the durability design project is the definition of the use class, which is based on the environmental exposure expected of the wood products. Table 21 presents the use classes' exposure and their susceptibility.

Table 21 - Use classes definition

Use class	Exposure	Biological agents*
UC 1	Inside construction (not exposed to the weather or wetting)	Beetles, Termites
UC 2	Under cover (not exposed to the weather, but occasional contact with humidity)	Beetles, Termites, Fungi
UC 3.1	Exposed to humidity for short time periods (above ground)	Beetles, Termites, Fungi
UC 3.2	Exposed to humidity for long time periods (above ground)	Beetles, Termites, Fungi
UC 4	Direct contact with ground and fresh water	Beetles, Termites, Fungi
UC 5	Direct contact with saltwater	Beetles, Termites, Fungi, Marine borers

* The event of biological agents depends on the geographical location and specific exposure conditions

The second step is the choice of wood species, which, besides the structural and economic criteria, may also depend on its natural durability, which is defined as the natural ability of wood to resist biological wood-destroying agents. A methodology is proposed by EN 350 (CEN, 2016b) to test and classify the durability of species against biological agents (durability class). According to this standard, sapwood is considered as not durable and, because of that, the durability classification is only given to heartwood.

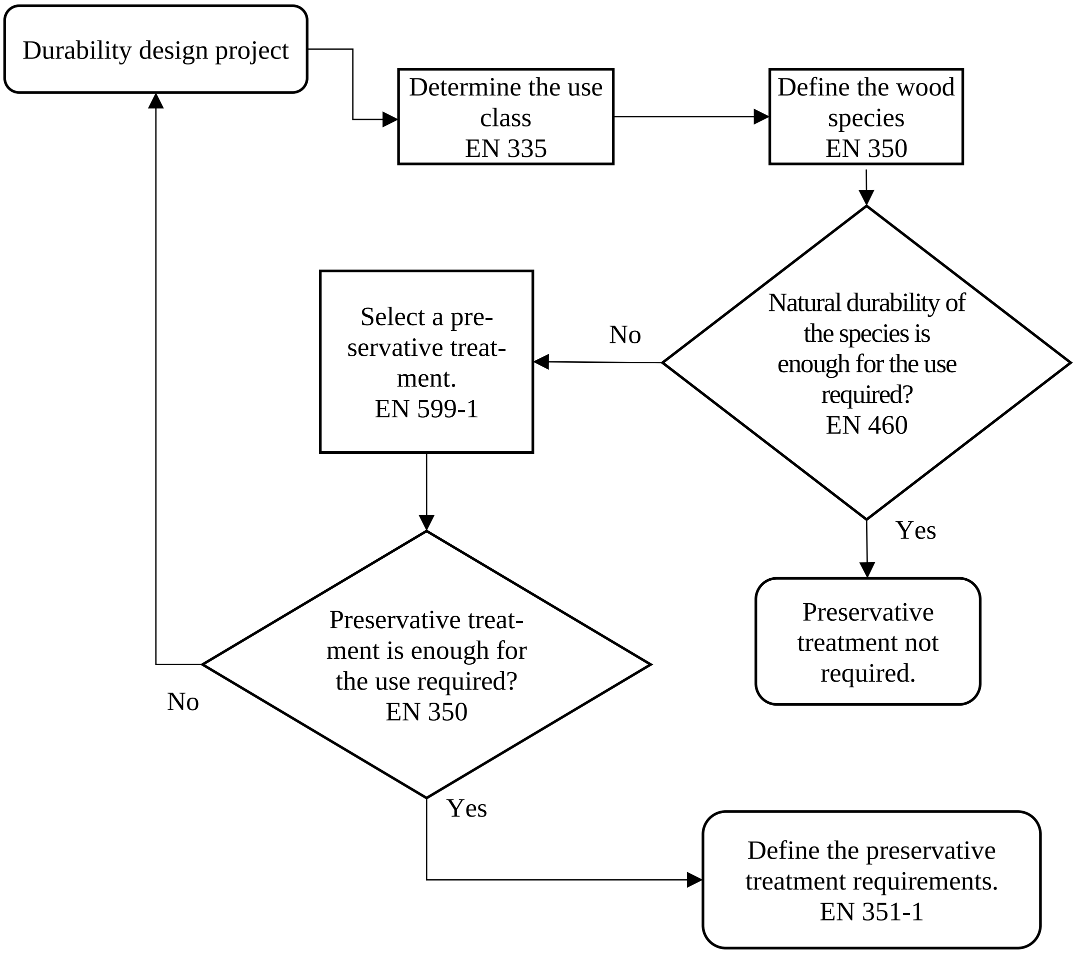

Figure 21 - Durability design procedure (adapted from EN 351-1 (CEN, 2007)).

After choosing the wood species, it is necessary to check whether the corresponding natural durability is sufficient for the use class, according to EN 460 (CEN, 1994). If this durability is not enough to guarantee the durability of the wood elements, a preservative treatment shall be used, for which EN 351-1 (CEN, 2007) considers two types of application: penetrating or/and surface. The former consists in applying the liquid treatment through cycles of vacuum and pressure or just vacuum in autoclave, while the latter is applied through brushing, spraying or immersion. Recently, new types of treatment based on wood modification methodologies have been developed (such as thermal modification (Lunawood®) and chemical modification (Accoya®) (Spear, 2015).

3.5.2 Preservative treatments

The selection of a preservative treatment shall be done based on EN 599-1 (CEN, 2013b). This standard suggests that the preservative treatment can be applied in three ways: surface application; impregnation application; and the combination of both. Although wood modification processes are increasingly used for the treatment of wood products, their production and use are not yet regulated by European standards. For that reason, the modification treatments are excluded from the scope of this study.

For impregnation and surface treatments, for a given use class, EN 599-1 (CEN, 2013b) refers the tests and procedures that shall be realized and the requirements that shall be accomplished. This work will not focus on these requirements because this information is presented in technical files and certification reports of the preservative treatments.

3.5.2.1 **Penetration treatments**

Based on EN 351-1 (CEN, 2008), the penetrating treatment is a process that includes procedures that intend to overcome the natural resistance of wood to the impregnation of preservative treatments in wood. This type of treatments is applied by autoclave, cycles of vacuum and pressure, so that the preservative product will penetrate the wood.

The amount of preservative product (kg) in wood (m^3) determines the toxicity of the products regarding the biological agents and consequently the ability of a product to be used for a specific use class. The penetration treatment assessed in this study was “Tanalith E 8001”, manufactured by “Lonza Cologne GmbH®” and authorized in Portugal under the number PT/DGAV ARMPB08-012/2018.

3.5.2.2 **Surface treatment**

Surface treatment application is defined by EN 351-1 (CEN, 2008) as a process that does not require the penetration of a preservative treatment to overcome the limited natural durability of wood. Usually, the application of treatment is by brushing, sprinkling or immersion.

Surface treatment application is quantified by the ratio of amount of product (l or kg) by surface of wood (m^2). The application of products shall follow the rules and methodology presented by technical files of products. The surface treatment assessed in this study was “Xylophene S.O.R.2 Extreme”, manufactured by “PPG AC France®” and authorized in Portugal under the number PT/DGAV ARMPB08-030/2019.

3.6 **Conclusions**

This chapter started by reviewing the biological structure of wood, followed by its visual, physical and mechanical properties. The mechanical properties of wood elements can be determined through visual and mechanical grading methodologies. Visual grading methodologies grade wood elements by strength classes based on their visual characteristics, to which mechanical properties are assigned based on results of destructive tests performed previously for specific wood species and growth area. Mechanical grading methodologies assign a strength class to a wood piece by quantifying the bending or tension properties of wood elements. After performing tests, a statistical procedure defines one or more combinations of one, two or three strength classes for which each combination of wood species and country of origin is suitable to be classified. The output of this process is a range of grading machine settings that enables the producers to determine the strength class of each wood element through non-destructive tests.

The visual grading strength classes suitable for Norway spruce from Sweden and Germany, Scots pine from Sweden and Germany, Maritime pine from Portugal, Cryptomeria from Portugal and Eucalyptus from Portugal were identified in this study. As the mechanical grading reports are confidential, only the Maritime pine mechanical grading data (including yield of each strength class) was obtained (through the grading report produced by the University of Coimbra). The bending strength and mean modulus of elasticity values for each combination of wood species and country of origin were identified in the literature review.

The strength and stiffness properties of strength classes of SW, GLT, LVL and IJ products given by European standards (or performance documents made based on European standards) were identified and presented in this chapter. Structural and durability design procedures given by European standards were reviewed and summarised in this chapter. Structural design consists of the quantification of loads and load combinations, quantification of material properties and structural analysis. Durability design consists of the determination of use class, definition of wood species and selection of preservative treatment.

4 COMPARISON OF STRUCTURAL PRODUCTS AND SOLUTIONS

4.1 General

A fair comparison of the environmental performance of structural products must consider their structural performance. The structural performance of wood-based products is quantified through strength classes (for SW and GLT) and strength and stiffness properties (for LVL and I-Joist). In general, higher strength and stiffness lead to a reduction of the volume of products required to meet the specified design requirements.

The literature review made in Chapter 2 identified a lack of information on the structural performance of wood-based products assessed and compared in LCA studies and EPDs. Without this information, the environmental comparison between structural products and solutions performed by LCA experts and/or engineers and/or architects did not consider the main function and application of these products.

According to the EN 15978 (CEN, 2011a), the environmental comparison of construction products can be performed at two levels: i) at the product level, and ii) at the building or building assembly level. This study proposes three methodologies to compare structural wood-based products and assembled systems for wood-based floors. Additionally, an approach to compare the environmental performance of durability solutions is also proposed.

In order to compare the environmental performance of structural products with the same strength class, this study proposes two approaches to estimate the strength classes of SW products (based on visual and mechanical grading). At the product level, this study also proposes a methodology to compare the structural performance of products by defining two equivalent functional units (based on bending strength and modulus of elasticity). At the structural level, the comparisons are performed by calculating: i) the volume of structural products required to fulfil the same structural requirements; and ii) the amount of preservative product and wood volume required to fulfil the same durability requirements.

4.2 Product level

This study proposes two methodologies to estimate the strength classes of SW products based on grading methodologies given by EN 14081-1 (CEN, 2016a): i) visual grading methodology, and ii) mechanical grading methodology. The application of these methodologies requires the previous identification of **wood species** and of the **geographical representativeness** intended for the study.

4.2.1 Visual grading

This section describes the methodology for estimation of strength classes based on the information available on studies that quantified the modulus of elasticity and density of datasets. In addition, this section applies the methodology to each combination of wood species and country of origin of SW products given in Section 3.3.

4.2.1.1 Method for estimation of strength classes

This methodology intends to estimate the strength cases of SW by following an approach based on visual grading methodology. This approach requires the identification of wood species, country of origin, mean modulus of elasticity and mean density for each dataset. This information can be found on EPDs, LCA reports and other support documents with the same representativeness (wood species and country of origin) as the aim of the study. The aim of this methodology is to estimate a single strength class for each dataset.

The methodology consists of two steps: i) collection of information about the dataset, and ii) determination of strength classes. The first step identifies the information given in dataset technical files and collects the information required by the methodology. Second step attributes a strength classes to dataset based on the data provided by EN 1912 (CEN, 2012b).

4.2.1.1.1 Collection of data from datasets

The data collected from datasets is intended to be used for the definition of the strength classes of each product. Whenever possible, the collection of information from SW datasets shall identify:

- Mean value of modulus of elasticity,
- Mean value of density of the products (at 12% of MC),
- Strength class or mechanical properties (if provided).

It shall also be identified whether the dataset is made for one specific product or for a group of products and whether datasets give single values or a range of values for the mechanical properties or strength class. To ensure structural comparability, the products that have not been produced according to EN 14081-1 (CEN, 2016a) European standard or equivalent shall be excluded.

4.2.1.1.2 Estimation of strength classes

This stage intends to determine the strength classes based on the information available in the dataset technical files, as indicated in Figure 22. If the dataset technical files provide a strength class for the product assessed, it can be assumed that the mechanical properties are given. If the dataset technical file provides more than one strength class for the products, or a range of classes, or does not give information about the strength classes, then the strength classes must be estimated. The information about the path followed to obtain the strength classes (estimated or given) shall be always clear whenever this methodology is applied.

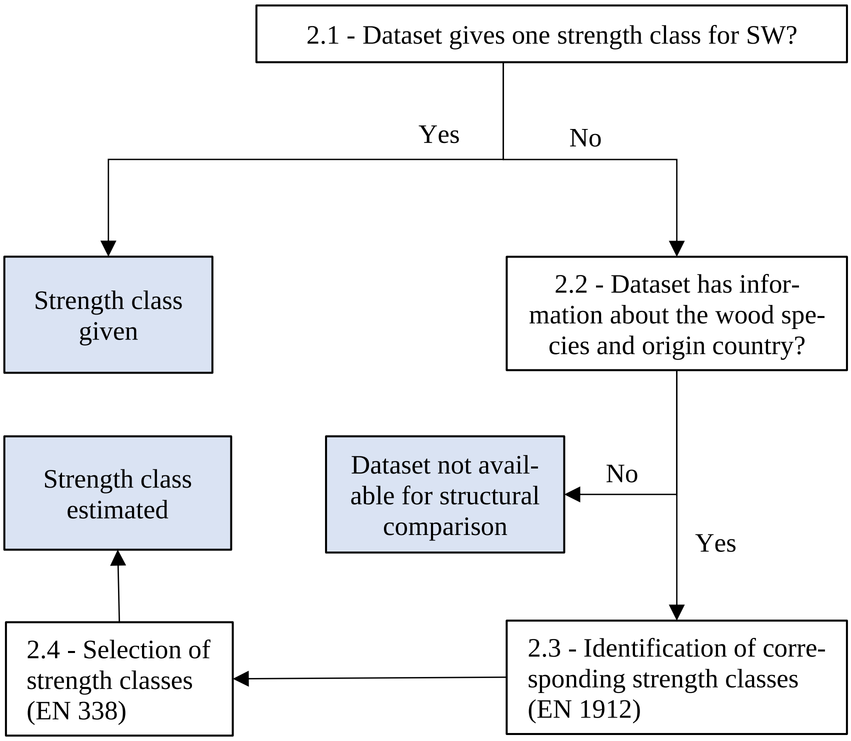

Figure 22 - Graphical representation of the SW strength classes' determination

The SW strength classes' determination stage is based on EN 14081-1's grading methodologies. Firstly, it shall be confirmed whether the dataset technical file provides the strength class, or the mechanical properties of the product assessed (stage 2.1). If so, the strength class shall be assumed as "given". If the dataset technical file provides a range of strength classes or the mechanical properties (including the minimum and maximum values) or does not give any information about the mechanical properties or strength classes, then stage 2.2 follows.

In stage 2.2, it shall be assessed whether the dataset technical file has information about the wood species and country of origin. If the dataset technical file does not provide both data, then it shall be excluded from this analysis. If the dataset technical file has information about the country of origin of wood and the wood species used in production, then stage 2.3 shall follow.

In stage 2.3, the available strength classes for combination of species and origins are identified, following the grading information given in EN 1912 (CEN, 2012b). All strength classes available for all combinations of wood species and countries of origins mentioned in the dataset technical files shall be determined.

The strength classes' selection (stage 2.4) is made through a correspondence of mean modulus of elasticity and mean density of products assessed with possible strength classes identified in stage 2.3. The values of properties for each strength class are given by EN 338. The strength class (identified in stage 2.3) with a modulus of elasticity and density just below the mean values of the dataset technical file shall be chosen. If the mean values of density and modulus of elasticity are lower than the values of the lowest strength class, then the dataset will not be available for comparison. The strength classes determined in stage 2.4 shall be identified as "estimated" and shall correspond to the strength classes or the mechanical properties identified in dataset technical files (in stage 1). If they do not, a strength class identified for the dataset with lower mechanical properties than the class estimated shall be chosen.

The strength class determined at the end of this methodology is representative of the complete dataset assessed. This representation can be used to compare the environmental impacts of datasets with similar strength classes.

4.2.1.2 Estimation of strength classes

This section estimates the strength classes of six datasets: Spruce from Sweden and Germany, Scots pine from Sweden and Germany, Maritime pine from Portugal, Cryptomeria from Portugal and Eucalyptus from Portugal. The collection of data from datasets was performed in Section 3.3 and identified the mean modulus of elasticity and mean density of each dataset. The results are summarized in Table 22.

Table 22 – Mean modulus of elasticity and density of various wood species and country of origin combinations

Wood species	Country	Modulus of elasticity [N/mm^2]	Density (at 12% of MC) [kg/m^3]
Spruce	Sweden	12300	435
Spruce	Germany	12100	441
Scots pine	Sweden	11300	481
Scots pine	Germany	11900	493
Maritime pine	Portugal	12900	597
Cryptomeria	Portugal	6189	309
Eucalyptus	Portugal	18151	905

As none of the sources of data identified in Table 22 has given a specific strength class for each dataset, then in step 2.1 the answer was "No" for all datasets and the step 2.2 was followed. As the wood species and country of origin were identified before for each dataset, then the stage 2.3 was followed, and the corresponding strength classes of each dataset were determined.

The strength classes identified by EN 1912 (CEN, 2012b) available to be visually graded for each combination of wood species and origin country are shown in Table 23. The grades of Maritime pine and Cryptomeria given by National grading standards (NP 4305 (IPQ, 1995)) and NP 4544 (IPQ, 2015)) were also considered.

Finally, in stage 2.4, the strength classes identified for the density and modulus of elasticity mean values of each combination of wood species and country of origin were identified. The results are shown in Table 23.

Table 23 – Strength classes given and identified for various wood species and country of origin combinations

Wood species	Country	Strength classes given by EN1912 (stage 2.3)	Strength classes identified (Stage 2.4)
Spruce	Sweden	C30, C24, C18, C14	C24
Spruce	Germany	C30, C24, C18	C24
Scots pine	Sweden	C30, C24, C18, C14	C24
Scots pine	Germany	C30, C24, C18,	C24
Maritime pine	Portugal	C30*, C24*, C18	C30
Cryptomeria	Portugal	C14*	C14
Eucalyptus	Portugal	D40	D40
***- strength classes identified by national grading standards**			

Although the mean values for modulus of elasticity and density of Cryptomeria are lower than the values given for C14 for those properties, the Cryptomeria dataset was included as C14 (lowest strength class identified by European standards) in this assessment. Spruce and Scots pine strength classes were C24. Maritime pine was identified as C30 and Eucalyptus was identified as D40.

4.2.2 Mechanical grading

This method intends to estimate the strength classes of SW datasets by using data resulting from the mechanical grading methodology given by EN 14081-2 (CEN, 2018a) and EN 14081-3 (CEN, 2018b). This study considered the reports and/or studies made to grade the wood pieces of a wood sample. In contrast to the method presented before, which gives one strength class for each scenario of wood species and country of origin, in this case a range of strength classes for each scenario is given.

This method intends to quantify the percentage of wood elements that corresponds to each strength class – quantified through published mechanical grading reports and/or academic studies. This percentage is used for allocation procedures during the LCI stage of the LCA methodology. In other words, this method identifies the combinations of strength classes of a wooden sample and calculates the percentage of wood elements that can be assigned to each specific strength class.

Firstly, studies and/or reports that performed destructive tests or mechanical grading for the determination of strength classes of wood samples shall be found in literature. This information must be collected for the wood species and geographical representativeness of the products that the study aims to compare.

The data that must be identified in each study and/or report are: i) the combination of strength classes considered in the mechanical grading procedure and ii) the percentage of wood pieces allocated to each strength class. The percentage of each strength class is collected to allocate the inputs and outputs within the system boundary to each strength class.

4.2.2.1 Method for the estimation of strength classes

4.2.2.1.1 Collection of data – identification of combinations of data

This step consists in the collection of data regarding the datasets to be used in environmental comparisons. For each combination of wood species and country of origin, this information can be found in reports and/or studies that performed destructive tests for the determination of bending or tension properties and/or strength classes of wood. Usually, studies and reports developed for mechanical grading perform these tests and, when published, they provide information that can be considered on this methodology.

The collection of data for each combination of wood species and country of origin shall identify:

- Combinations of strength classes reported,
- For each combination of strength classes, the percentage and/or amount of wood pieces that belonged to each strength class.

4.2.2.1.2 *Allocation of strength classes – based on tests results*

The values of percentage and/or the number of specimens of each strength class are used to allocate the environmental impacts per cubic meter of wood to the strength classes determined. The allocation shall model the amount of wood pieces that corresponds to each strength class in a wood sample.

When various combinations of strength classes are identified, the combination that considers the highest number of strength classes shall be used. In the case of various combinations with the same number of strength classes, the combination that includes strength classes with the lowest difference of strength and stiffness properties between them (for example, the use of a C18/C24/C35 combination instead of a C18/C24/C40 combination) must be considered.

The allocation procedure is applied by considering a grading stage at the end of production stages which considers the complete wood sample as input and the amount of each strength class graded as output. At the end of this methodology, the environmental impacts of a wood sample can be allocated to each strength class of SW.

4.2.2.2 **Estimation of strength classes**

The collection of data considers the mechanical grading results found on the literature review made in Section 3.3 for Maritime pine from Portugal. The combination of strength classes used in the allocation of strength classes is shown in Table 24.

Table 24 – Yield of Maritime pine strength classes used for mechanical grading allocation

Wood specie	Combinations assumed	Strength class	Yield [%]
Maritime pine	C35/C24/C18/Rejected	C35	81.9
		C24	6.9
		C18	6.6
		Rejected	4.6
		Total	100.0

The proposed allocation procedure modelled a process for each strength class, assuming that the output was the amount of wood from a sample that was able to be used as a specific strength class. The percentage of wood able to be used as a specific strength class (allocation yield) was calculated by dividing the amount of the wood sample (for example, 1 m^3) per summed yield of wood able to be used as a specific strength class. The summed yield of wood able to be used as a specific strength class was calculated by summing the yield of wood classified with a higher strength class than the strength class that is being calculated. The allocation yield of rejected wood was considered 100.0% because all the other wood can be used as ungraded wood. The representation of this allocation procedure was shown in Figure 23.

For example, to calculate the allocation yield of C24 strength class of Maritime pine, firstly the summed yield of C24 strength class shall be calculated by summing the yield of C35 and C24 strength classes (81.9% + 6.9% = 88.8%). Thus, to calculate the allocation yield used for environmental allocation procedures of class C24, the total volume of wood sample graded (considered 1.0 m^3) shall be divided by the summed yield (1 m^3/88.8%=112.6%). This percentage represents the cubic metres of wood that it is necessary to saw to obtain one cubic metre of wood of this structural class. In this case, to obtain 1 m^3 of C24 it is necessary to saw 1.126 m^3 of Maritime pine wood. Finally, to obtain the environmental impacts of C24 strength class, the environmental impacts per cubic meter of wood shall be multiplied by the allocation yield of C24 strength class.

The values of Maritime pine grading methodology are shown in Table 25. The environmental impacts of various strength classes are calculated in Section 8.2.4.

Table 25 – Yield of strength classes used for allocation of environmental impacts

Strength class	Yield [%]	Summed yield [%]	Allocation yield [%]
C35	81.9	81.9	122.1
C24	6.9	88.8	112.6
C18	6.6	95.4	104.8
Rejected	4.6	100.0	100.0
Total	100.0	-	-

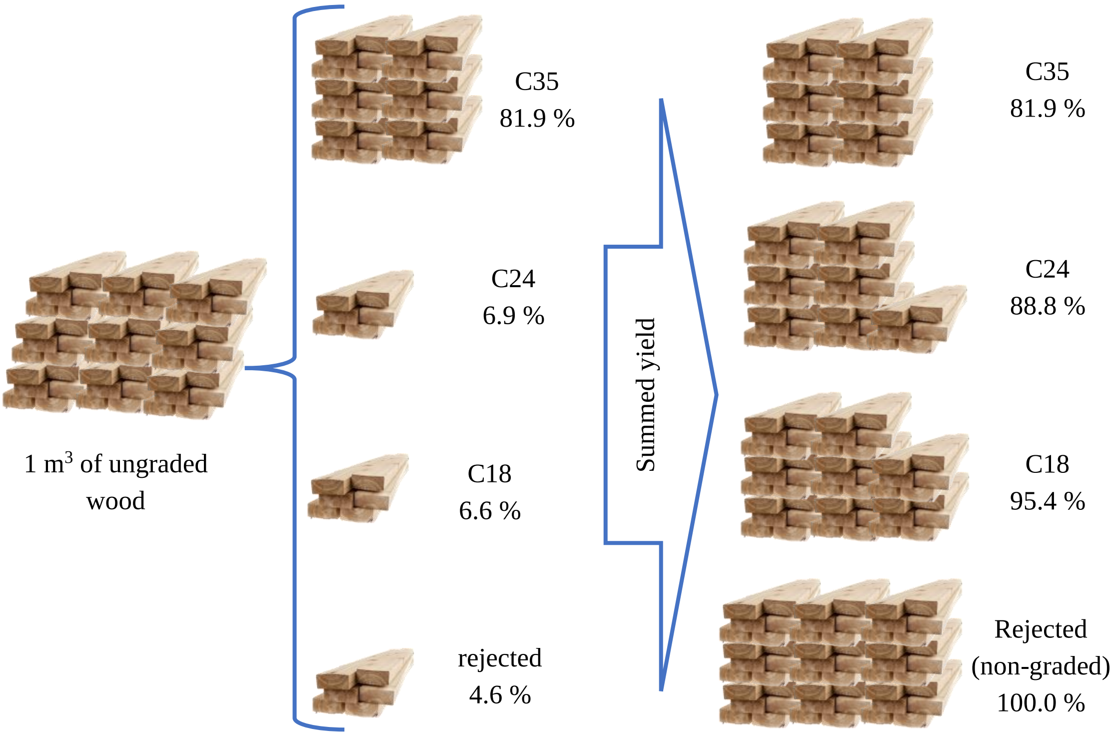

Figure 23 – Scheme of the calculation of summed yield for mechanical grading methodology

4.3 Bending strength and modulus of elasticity equivalent units

The methodology proposed in this section intended to define two equivalent units for environmental comparison of structural products by taking into account the bending strength and the modulus of elasticity of wood-based products. Those properties can be found on studies and/or reports that quantified these properties for SW, GLT, LVL, or other structural wood-based products with a rectangular cross section.

This section describes the method for the definition of a bending strength equivalent unit and a modulus of elasticity equivalent unit. Those units were used to compare the volume of SW required to fulfil the equivalent units defined. The procedures for the determination of both equivalent units are similar and are explained in the following subsections. The bending strength and the modulus of elasticity equivalent units were calculated for the various wood species and countries of origins given in Section 3.3, and for GLT and LVL products.

4.3.1 Definition of the bending strength and modulus of elasticity equivalent units

The determination of the bending strength and modulus of elasticity equivalent units consist of the calculation of the volume of a specific product required to fulfil the requirements of a unit case study (described below). The volume calculated was used as the basis for the comparison of various scenarios and was described as the equivalent volume. The calculation of the bending strength and of the modulus of elasticity equivalent volumes consists of two steps: i) collection of data from studies and/or reports that quantified bending strength and/or modulus of elasticity of wood-based products, and ii) the determination of the equivalent volume.

4.3.1.1 Collection of data about bending properties

Firstly, studies and/or reports in literature that quantify, through destructive tests, the bending strength and/or the modulus of elasticity of wood-based products must be found. Those documents must have the same representativeness (geographical and technical) as the aim of the study. For these materials, the average bending properties (modulus of elasticity and bending strength) must be determined in accordance with the procedures given by EN 384 (CEN, 2018c) and EN 408 (CEN, 2012c) for determining mechanical properties.

4.3.1.2 Determination of the equivalent volume

The calculation of the equivalent volume consists in the determination of the volume of structural products required to comply with the bending tension, and short-term deflection for a case study that assume unitary values in some design variables, such as length and distribute load applied. The case study considers a simply supported beam with a length of 1 meter submitted to a distributed load of 1 kN/m as shown in Figure 24. The checks to be made are those given by EN 1995-1-1 (CEN, 2014c), for bending strength and modulus of elasticity, respectively. The procedures for the determination of the bending strength and modulus of elasticity equivalent volumes are described in the following subsections.

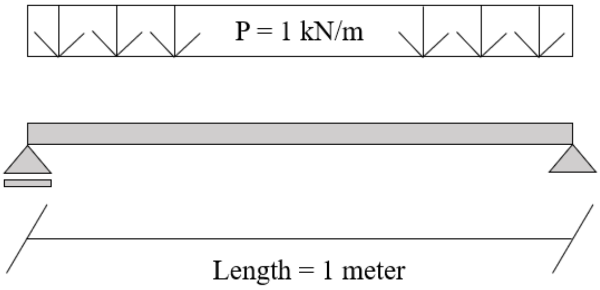

Figure 24 – Unit case study used in the calculation of the equivalent volume

4.3.1.2.1 Bending strength equivalent volume

The bending strength equivalent volume is determined by using the equations given in section 6.1.6 of EN 1995-1-1 (CEN, 2014c), which is shown below (Equation 5). The design stress is the bending tension applied in the structure subjected to a unit action (1 kN/m). This tension is calculated according to the most common models from the fields of Strength of Materials and Theory of Structures. The equations for determining the design stresses are those shown in Equations 6 and 7. According to the definition, the equivalent volumes are defined based on a unit case study, where the length of the beam is 1 meter. This simplification is shown in Equations 8 and 9.

$$\sigma_m \leq f_m \tag{5}$$

$$\frac{M_f \times h}{2 \times I_y} \leq f_m \tag{6}$$

$$\frac{\frac{P \times l^2}{8} \times h}{2 \times \frac{w \times h^3}{12}} \leq f_m \tag{7}$$

$$\frac{\frac{1 \times 1^2}{8} \times h}{2 \times \frac{w \times h^3}{12}} \leq f_m \tag{8}$$

$$\frac{3}{4 \times w \times h^2} \leq f_m \tag{9}$$

Where:
σ_m is the design bending stress,
f_m is the design bending strength,
M_f is the bending moment,
I_y is the moment of inertia,
h is the height of beam cross section,
w is the width of beam cross section,
l is the length of the beam,
P is the distributed load.

As the σ_m is a known variable, given by reports and/or other studies, Equation 9 has two design variables (w and h). In order to calculate the minimum cross section that fulfils the structural requirements, the design variables of Equation 5 shall be reduced to one. For simplification purposes, a ratio of 2 between the height and the width of the cross section (height is equal to two times the width) is assumed. This assumption is commonly used in the design of SW structures. For structures using other products, a higher ratio is usually used. In order to ensure equivalence, the same ratio is maintained in the various products.

This substitution is made in Equation 9 and is simplified in Equations 10 and 11. Using Equation 11, it is possible to estimate the minimum height of the beam and, consequently, the equivalent volume.

$$\frac{3}{4 \times \frac{h}{2} \times h^2} \leq f_m \tag{10}$$

$$\sqrt[3]{\frac{3}{2 \times f_m \times 1000}} \leq h \tag{11}$$

4.3.1.2.2 Modulus of elasticity equivalent volume

The modulus of elasticity equivalent volume is determined by the procedures given in section 7.2 of EN 1995-1-1 (CEN, 2014c). In this study, the most common limiting verification for deflections is considered – instantaneous deflections (Equation 12). The deformation is calculated according to the most common models from the fields of Strength of Materials and Theory of Structures. Based on those models, the equation for the determination of the cross section is shown in Equation 13. Like the calculation of the bending strength equivalent volume, this calculation assumed a unit case study, with unit values for distributed loads and length of the beam. Thus, Equation 17 shows the simplification of those equations.

$$def_m \leq def_{máx} \tag{12}$$

$$\frac{5 \times P \ \times l^4}{384 \times E_m \times I_y} \leq def_{máx} \tag{13}$$

$$\frac{5 \times P \ \times l^4}{384 \times E_m \times \frac{w \times h^3}{12}} \leq def_{máx} \tag{14}$$

$$\frac{5 \times 1 \ \times 1^4}{384 \times E_m \times \frac{w \times h^3}{12}} \leq def_{máx} \tag{15}$$

$$\frac{5}{32 \times E_m \times w \times h^3} \leq def_{máx} \tag{16}$$

$$\frac{5}{32 \times def_{máx} \times w \times h^3} \leq E_m \tag{17}$$

Where:
def_m is the deformation in the middle span,
$def_{máx}$ is the maximum deformation in the middle span,
E_m is the modulus of elasticity,
I_y is the moment of inertia,
h is the height of the beam cross section,
w is the width of the beam cross section,
l is the length of the beam,
P is the distributed load.

For the calculation of $def_{máx}$, the mean value for the limiting values of instant deformation given by EN 1995-1-1 (CEN, 2014c) is considered, being the length of the beam (1000 mm) divided by 400 (1000/400=5/2). The same simplification made before (on the bending strength equivalent unit) for the determination of the cross section is assumed. Thus, the width of the cross section is calculated by dividing the height by 2. Those values are substituted in Equation 17 and are shown in Equation 18 and simplified in Equation 19.

$$\frac{5}{32 \times \frac{5}{2} \times \frac{h}{2} \times h^3} \leq E_m \tag{18}$$

$$\sqrt[4]{\frac{1}{8 \times E_m \times 1000}} \leq h \tag{19}$$

The minor height value calculated with equations 11 and 19 must be used in the calculation of the equivalent volume. The equivalent volume is calculated by multiplying the cross-section area [m^2] by the length of beams (1.0 m). To compare the environmental impacts of various solutions, the volume calculated must be multiplied by the environmental impacts per cubic meter of product.

4.3.2 Comparison of equivalent volume

The methodology already proposed before applied in this section to compare the structural performance of the sawnwood scenarios described in Section 3.3 and of the GLT and LVL given in Section 3.4. GLT and LVL were excluded from the bending strength equivalent volume comparison due to the lack of data. In contrast, these products were considered in the calculation of the modulus of elasticity equivalent volume. This study assumed the mean values of GL24h strength class for GLT and the mean values of KertoS® for LVL. The bending strength and modulus of elasticity of each dataset are shown in Table 26.

The bending strength and modulus of elasticity equivalent volume were calculated using the equations 11 and 19 and the data given in Table 26. The volume of equivalent units is shown in Table 27. The relative comparison of bending strength and modulus of elasticity functional units are shown in Figure 25.

Figure 25 shows that the Cryptomeria scenario had the highest equivalent volume for both functional units. The Eucalyptus had the lowest equivalent volumes on both functional units. The Maritime pine was the softwood scenario with the lowest equivalent volume on both functional units studied. For non-SW products, LVL required a lower amount of volume than GL24h. The environmental impacts of various products for both equivalent units are compared in Chapter 8.

Table 26 – Bending strength and modulus of elasticity of various SW, GLT and LVL scenarios studied

Wood species	**Origin**	**Bending strength**	**Modulus of elasticity**
Units		N/mm^2	N/mm^2
Spruce	Sweden	44,8	12300
Spruce	Germany	41,5	12100
Scots pine	Sweden	44,7	11300
Scots pine	Germany	38,6	11900
Maritime pine	Portugal	54,1	12900
Cryptomeria	Portugal	26,0	6189
Eucalyptus	Portugal	75,9	18151
GL24h	Europe	-	11600
LVL	Europe	-	13800

Table 27 – Height of cross sections and equivalent volumes of various SW, GLT and LVL scenarios

Wood species **Origin**		**Bending strength**		**Modulus of elasticity**	
		Height	Volume	Height	Volume
Units		m	m^3	m	m^3
Spruce	Sweden	3.22E-02	5.19E-04	1.00E-02	5.04E-05
Spruce	Germany	3.31E-02	5.47E-04	1.01E-02	5.08E-05
Scots pine	Sweden	3.23E-02	5.20E-04	1.03E-02	5.26E-05
Scots pine	Germany	3.39E-02	5.74E-04	1.01E-02	5.12E-05
Maritime pine	Portugal	3.03E-02	4.58E-04	9.92E-03	4.92E-05
Cryptomeria	Portugal	3.86E-02	7.47E-04	1.19E-02	7.11E-05
Eucalyptus	Portugal	2.70E-02	3.65E-04	9.11E-03	4.15E-05
GL24h	Europe	-	-	1.02E-02	5.19E-05
LVL	Europe	-	-	9.76E-03	4.76E-05

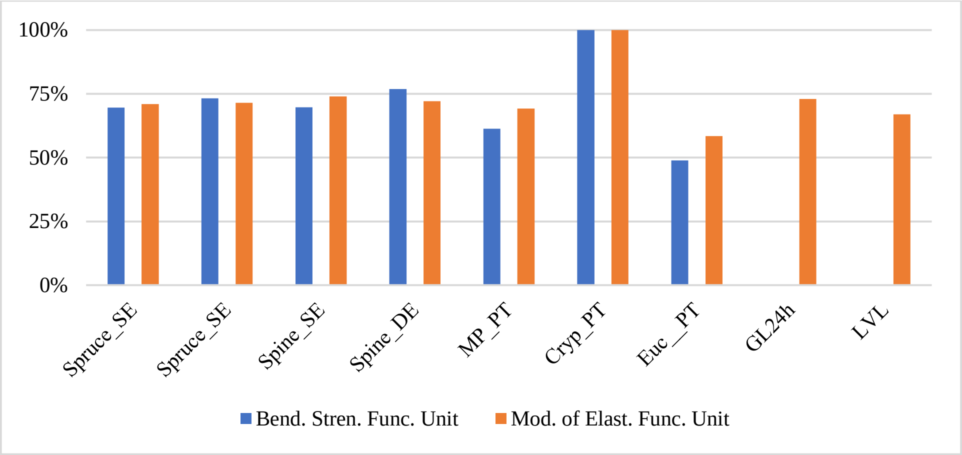

Figure 25 – Comparison of the relative values of equivalent volumes of various SW, GLT and LVL scenarios

4.4 **Structurally equivalent functional unit**

In this section, a method to define a structurally equivalent functional unit for floors designed with wood and/or wood-based products was proposed. The structurally equivalent functional unit was defined by the minimum volume of wood and/or wood-based structural product that complies with the structural requirements and rules given by EC0 (CEN, 2011b) and EC5 (CEN, 2014c).

This method was divided into five main steps: 1) definition of the functional equivalence, 2) definition of design variables, 3) structural analysis, 4) design, and 5) volume of structural products. They were illustrated in Figure 26.

4.4.1 Definition of structural unit

4.4.1.1 Definition of the functional equivalence (Step 1)

The “functional unit” is defined by ISO 14040 (ISO, 2006b) as the quantification of identified functions or performance characteristics of products. At the building level, the quantification of technical characteristics and functionalities shall be made by defining a functional equivalence, which shall include, according to EN 15978 (CEN, 2011a): building type, technical and functional requirements, a pattern of use and required service life. The functional unit and/or functional equivalence shall be clearly defined when the purpose of the study is to compare solutions with different technical characteristics.

In this method, the equivalence between the structural performance of alternatives is ensured by identifying and quantifying: i) structural requirements, ii) geometry, iii) environmental exposure of the wood elements, and iv) actions applied in the structure (and their combinations). This step intends to qualify and quantify the requirements imposed by the contracting authority or by the standards for those variables.

Table 28 lists the design variables that shall be identified and quantified at this step and the respective supporting documents. The following subsections describe each variable in more detail.

4.4.1.1.1 Structural Requirements and limitations (Step 1.1)

According to EN 1990 (CEN, 2011b), the design of a structure shall guarantee structural resistance, serviceability and, in case of fire, an adequate structural resistance during a required period. The structural resistance and serviceability shall fulfil the ULS and SLS requirements given in section 6 and section 7 of EN 1995-1-1 (CEN, 2014c), respectively. In addition, the design service life should also be specified (section 2.3 of EN 1990 (CEN, 2011b)). The fire design shall be made according to EN 1995-1-2 (CEN, 2011d).

In this method, all the requirements to fulfil must be defined and the respective limit values quantified. The contracting authority may require more demanding limitations than the limit values from the standards. For those cases, these limitations shall be described and quantified.

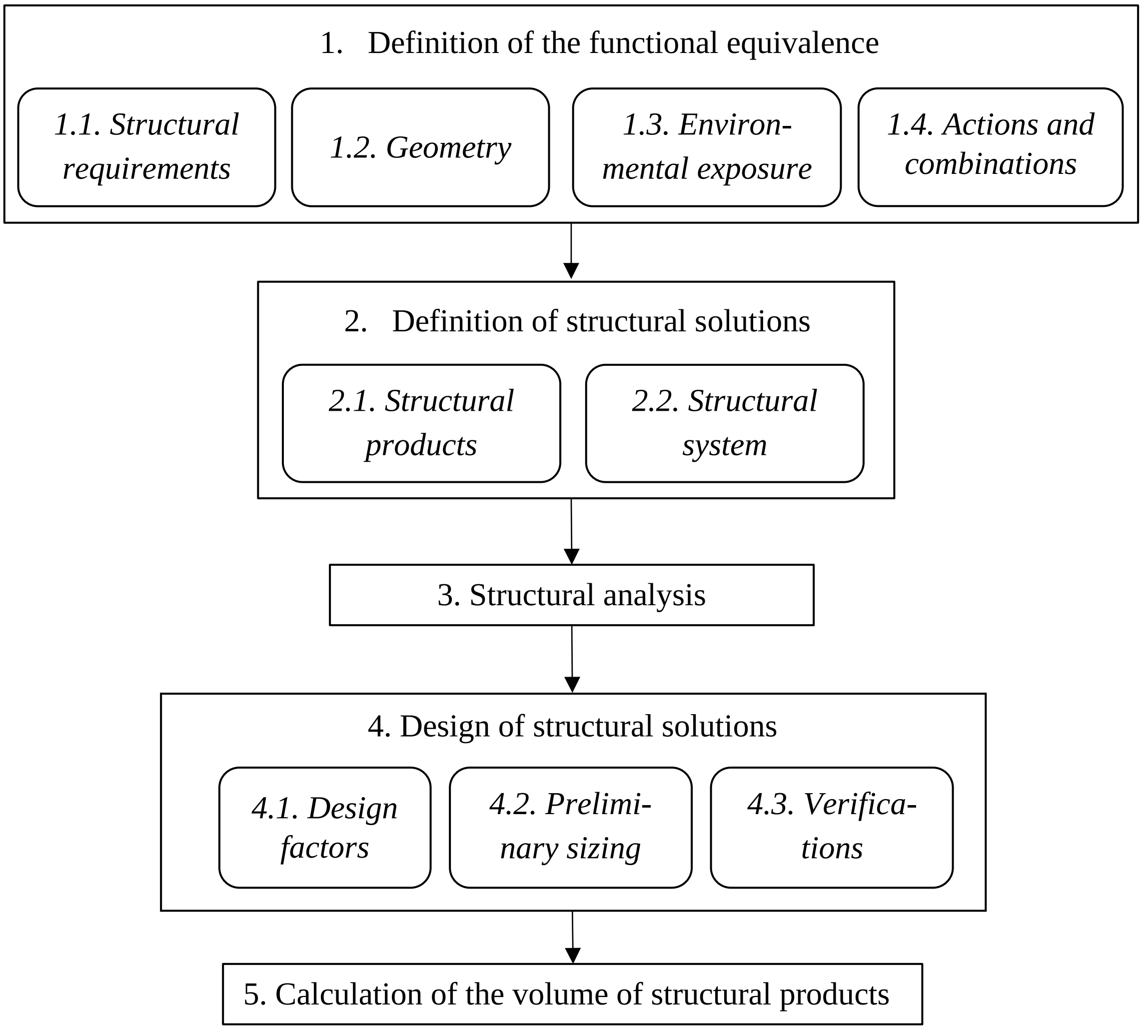

Figure 26 - Steps for the definition of a structurally equivalent functional unit for wood-based floors

Table 28 Design variables of Step 1 and respective supporting documents

Step	Variable	Supporting document
1.1 - Structural requirements	ULS requirements	EC5 (CEN, 2014c)
	SLS requirements	EC5 (CEN, 2014c)
	Fire requirements	EN 1995-1-2 (CEN, 2011d)
1.2 - Geometry	Floor dimensions (area, perimeter, etc.)	Contracting documents
	Floor shape	Contracting documents
1.3 - Environmental exposure	Service Class	EC5 (CEN, 2014c)
	Use Class	EN 335 (CEN, 2013b)
1.4 - Actions and combinations	Type of actions	EC0 (CEN, 2011b)
	Action values	EC1 (CEN, 2011c)
	Load duration class	EC5 (CEN, 2014c)
	Combination values	EC0 (CEN, 2011b)

4.4.1.1.2 Environmental exposure (Step 1.3)

The air temperature and relative humidity to which the wood elements are exposed during their use shall be quantified and the service class shall be identified according to section 2.3.1.3 of (CEN, 2011b). Service classes intend to incorporate, at the design stage, the effect of moisture content in the strength and stiffness of these materials.

The exposure of the structure to weather, wetting, ground, freshwater, and saltwater shall also be quantified and the use class defined by EN 335 (CEN, 2013b) shall be identified. The structural products, their wood species and the preservative treatments applied shall be chosen taking into account the use class of the products.

4.4.1.1.3 Actions and combinations (Step 1.4)

The actions and their combinations shall be determined and quantified according to EN 1990 (CEN, 2011b) and EN 1991-1 (CEN, 2011c). Based on their variation in time, actions shall be classified as permanent, variable or accidental. Actions shall be then quantified based on the values given by EN 1991-1 (CEN, 2011c). The self-weight of the products shall be quantified based on the density and dimensions of the corresponding material. As the dimensions of structural elements are not known at this point, the self-weight is estimated based on the experience and/or on rough approaches. After the “preliminary sizing” step, the cross-section dimensions shall be adjusted.

The strength of wood and/or wood-based products may decrease over time. In order to take this into account in the design, EN 1995-1-1 (CEN, 2014c) proposes a classification for load duration classes:

- Permanent: more than 10 years,
- Long-term: between 6 months and 10 years,
- Medium-term: between 1 week and 6 months,
- Short-term: less than one week,
- Instantaneous.

The combinations of actions for ULS verifications shall be determined according to sections 6.4.3.2, 6.4.3.3 and 6.4.3.4 of EN 1990 (CEN, 2011b). The combinations of SLS verifications shall be determined according to the section 6.5.3 of EN 1990 (CEN, 2011b).

4.4.1.2 **Definition of structural solutions (Step 2)**

The solutions designed may differ in their products and/or structural system. For each product, the strength and stiffness properties may also differ. At this step, the product and structural system variables are quantified, and the structural solutions are characterised.

4.4.1.2.1 Structural products (Step 2.1)

Wood and/or wood-based products used as structural products shall comply with the respective product standards or European regulation (for example, EN 14080 (CEN, 2013a) for GLT). Usually, the structural products are grouped in strength classes with different strength and stiffness values. Products not comprised within any harmonised European standard must be assessed by a “Declaration of Performance” document that provides strength and stiffness values to be used in their design.

4.4.1.2.2 Structural system (Step 2.2)

The structural system shall reflect the real configuration of wood elements and of their connections. According to Swedish Wood (2016), there are two main types of structural systems for planar building elements (such as floors): light frame systems and solid wood systems. Note that solid wood systems are not related to SW products, since solid wood solutions apply products with a higher technological level than SW products (e.g. CLT).

Light frame systems use parallel beams placed at even distances, usually with the voids filled with an insulation material, and covered by sheathing that protect the elements. The main structural products used in the systems are SW, GLT, IJ, and LVL. The use of these products limits the floor spans from 5 to 10 m (depending on the products). Beams made of these products can be combined with perpendicular beams (with higher cross-section or made with other material) to increase the span of structural systems. The variables of this type of structural system can be (but are not limited to): i) the configuration of the structural system (such as the number of beams, the spacing between beams, etc.); and ii) the beam supports and connections (simple, pinned, rolled or fixed).

Solid wood systems usually consist of a single structural product applied over the entire floor area. They are usually made with CLT elements. CLT is made of sawnwood glued in layers (3, 5 or 7) with the boards in each layer placed perpendicular to the layer above and below, although the overall section must be symmetrical. These panels can be manufactured in an extensive range of sizes, and the sizes are limited by transportation and manufacturing operations and by the geometry of the floor. The structural configuration variables of these solutions can be: i) the configuration of the structural system (such as openings) and ii) the layer support and connections.

4.4.1.3 **Structural analysis (Step 3)**

The structural analysis shall be performed in accordance with Section 5 of EN 1995-1-1 (CEN, 2014c). To do the verifications required by this standard, an elastic behaviour of the materials shall be assumed in the modelling of the global behaviour of the structure.

The structural behaviour of the elements shall be predicted by design models based on the fields of Strength of Materials and Theory of Structures.

At this step, it is necessary to quantify: i) the stresses imposed by actions (for ULS verifications) and ii) the deflections and vibrations (for SLS verifications). The quantification of the stresses and of the effects of *actions* and its *combinations* in the *structural products* shall be calculated taking into account the *geometry of the solution* and *of the structural system*.

4.4.1.4 **Design of structural solutions (Step 4)**

The design procedure follows the partial factor method, which checks whether both ultimate and serviceability limit states are exceeded by actions and/or by their effects. The structural design procedure proposed consists of three steps: calculation of design factors, preliminary sizing, and verifications.

4.4.1.4.1 Design factors (Step 4.1)

The design factors adjust the strength properties of structural products by multiplying (or dividing) the resistant value by a factor value that takes into account specific phenomena such as the unfavourable effects of geometrical deviations and of the uncertainty in the resistance of the products (given by γ_M: partial factor for product properties, imposed by EC0 (CEN, 2011b)). The γ_M values are given in table 2.3 of EN 1995-1-1 (CEN, 2014c). In addition to this factor, EN 1995 (CEN, 2014c) indicates that the modification factors that shall be calculated in floors design are: k_{mod} (modification factor for the duration of the load and moisture content), k_h (depth factor), $k_{c,90}$ (an increase factor of the compressive strength perpendicular to the grain), k_{crit} (a reduction factor for strength due to the effects of lateral buckling), k_m (modification factor that considers the redistribution of bending stresses in a cross-section), k_{sys} (an increase factor for structural strength), k_v (a reduction factor for notched beams), k_{vol} (a volume factor that adjusts the design tensile strength perpendicular to the grain in the apex zone of a double-tapered, curved or pitched beam), k_{cr} (a crack factor for shear resistance), and k_{def} (a deformation factor).

4.4.1.4.2 Preliminary sizing (Step 4.2)

The preliminary sizing (pre-sizing) consists of a preliminary approach of the cross-section of the structural system under design. Since the instantaneous deflection is often known as the most severe verification, it can be used to estimate the cross-section. Thus, the pre-sizing proposed by this study is based on the deflection caused by the actions calculated in Step 1.4 and on the deflection requirements imposed by the contracting authority or by standards.

Firstly, the two cross-section variables of light frame system's products (width and height) shall be reduced to one. This can be made by imposing a relation between width and height or using a rule based on the designer's experience to estimate one of these dimensions (for example: height = length / 20) (Borgström & Karlsson, 2016). SW systems design just have one variable (height of elements).

The instant deflection of each element shall be lower than the deflection limits defined at the requirements step. The procedure given by Section 7.2 of EN 1995-1-1 (CEN, 2014c) shall be applied. Based on this verification, the cross-section variable is estimated.

Wherever possible, the pre-sizing procedure shall be the same for every structural solution design. When a different procedure is followed (for example, for non-rectangular cross sections), it shall be clearly described.

4.4.1.4.3 *Verifications (Step 4.3)*

The ULS, SLS and fire behaviour requirements given in Step 1.2 must be complied with. For floors, the most common ULS requirements are bending, compression perpendicular to the fibres, and shear. The actions values are obtained from the structural analysis (Step 3) and the resistance values of materials shall be calculated according to section 3 of EN 1995-1-1 (CEN, 2014c). According to EN 1995-1-1 (CEN, 2014c), the SLS verifications that shall be made for floors design are vibrations and short-term and final deflection. These effects shall be determined, quantified and verified according to the procedures given in section 7 of EN 1995-1-1 (CEN, 2014c).

Fire verifications shall be made according to EN 1995-1-2 (CEN, 2011d). For the verification of the fire design, it is recommended to apply one of the simplified methods indicated by EN 1995-1-2(CEN, 2011d): cross-section reduction method or reduced properties method. Whenever the cross section pre-sized is not enough to comply with the requirements imposed, the cross-section variable shall be enlarged, and the verifications shall be made again.

4.4.1.5 **Calculation of the volume of structural products (Step 5)**

When all the requirements are complied with, the minimum volume of products for each structural solution designed must be calculated. That volume can then be used for comparisons between structurally equivalent solutions.

4.4.2 Case study - Residential interior floor

The method described in Section 4.4.1 is applied in this section to design various functionally equivalent structural scenarios that fulfil the described requirements; and to determine the volume of structural products required for each solution. This case validated the method proposed and compared the environmental impacts of various structural products commonly applied in Europe in light frame systems of floor structures for residential buildings.

4.4.2.1 Definition of the functional equivalence

4.4.2.1.1 Structural requirements

The ULS requirements that structural elements must meet were bending moment and compression perpendicular to the grain. SLS requirements are short- and long-term deflections and vibrations. The limit values for both were given by EN 1995-1-1 (CEN, 2014c).

It is considered that structural products were protected from fire by ceiling products. Therefore, the fire checks are excluded from the analysis. The durability of the products must be enough to maintain the structural performance of the products for 50 years when exposed to the environmental conditions is given in Step 1.3.

4.4.2.1.2 Geometry

The floor had a squared shape with 16 m^2 (4x4 m^2) of area and 16 m of perimeter. Figure 27 shows the geometry of the floor (plant view) and the configuration given by the contracting authority.

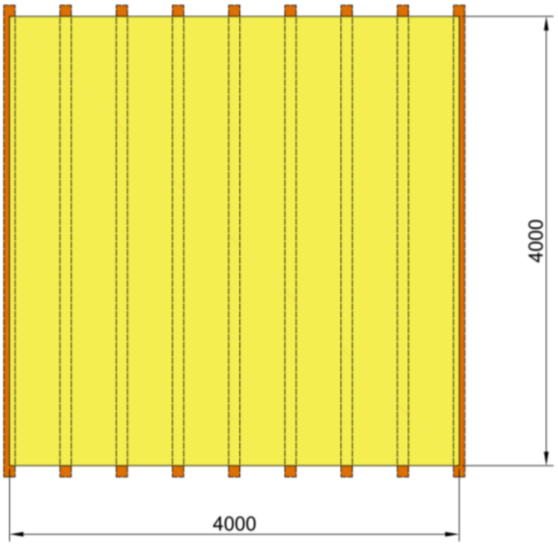

Figure 27 - Plan view of residential floor [mm]

4.4.2.1.3 Environmental exposure

The floor had a residential use and was installed according to the temperature and humidity conditions of Service Class 1 and Use Class 1. It was assumed that protective measures were installed on site to prevent attacks by degradation agents during the service life of the structure.

4.4.2.1.4 Actions and their combinations

The actions imposed on the structural elements were the self-weight of the structural products (beams and panel), the self-weight of the ancillary products and the actions imposed on a floor for residential use. These actions were quantified using EN 1991-1 (CEN, 2011c). Action values, type and duration classes are given in Table 29.

Table 29 Actions values, type and duration classes

Name	Value	Type	Duration class
Structural products weight	depends on product	Permanent	Permanent
OSB panel weight	0.15 kN/m^2	Permanent	Permanent
Ancillary products weight	1.00 kN/m^2	Permanent	Permanent
Residential load	2.00 kN/m^2	Variable	Long-term

The values of the combinations of actions were determined according to the EN 1990 (CEN, 2011b) procedure. The fundamental (ULS), the characteristic (SLS) and the quasi-permanent (SLS) combinations of actions were calculated. As their values depend on the products' densities and cross-sections, they were calculated and given in Section 4.4.2.4.

4.4.2.2 **Definition of the structural solutions**

The structural solutions varied in terms of the structural products used and of their corresponding strength and stiffness properties. The various structural scenarios are described below.

4.4.2.2.1 Structural products

SW, GLT, LVL and IJ products are considered as structural products. The SW structural solutions differ in terms of their wood species (softwood and hardwood) and strength classes (C18, C24, C30, C35 C40, and D24, D30, D35 and D40). GLT solutions differ in terms of their strength classes (GL24h, GL28h, and GL32h). Only one structural solution of LVL was considered (KertoS ®). Two different flange materials of IJ products were considered: C24 and LVL. The web of both was made of OSB/3. For all the solutions, an OSB/3 panel was considered as the planar product that distributes the loads to the beams. The structural solutions are summarized in Table 30.

SW and GLT strength and stiffness properties are given by EN 338 (CEN, 2009a) and EN 14080 (CEN, 2013a), respectively. Strength and stiffness properties of LVL are obtained in the respective DOP (Daas Baksteen, 2014). The strength and stiffness of flange materials are those given previously for each product and the strength and stiffness of web materials (OSB/3) are given by EN 12369-1 (CEN, 2001). The design of the IJ beams follows the procedures given by Annex B of EN 1995-1-1 (CEN, 2014c). Strength and stiffness properties, and the density of the various products were those given in Section 3.4.1.

Table 30 - Structural solutions designed

Structural products		Planar product
SW Softwood	C18	OSB/3
	C24	
	C30	
	C35	
	C40	
SW Hardwood	D24	
	D30	
	D35	
	D40	
GLT	GL24h	
	GL28h	
	GL32h	
LVL	LVL	
IJ	IJ (C24+OSB)	
	IJ (LVL+OSB)	

4.4.2.2.2 Structural configuration

The light frame structural products were designed considering that each beam element was simply supported and that they were spaced about 0.500 m (9 beams per floor). A thickness of 25 mm for the OSB/3 panel was previously checked in terms of the ULS and SLS requirements. The structural configuration of the light frame system floor is shown in Figure 28.

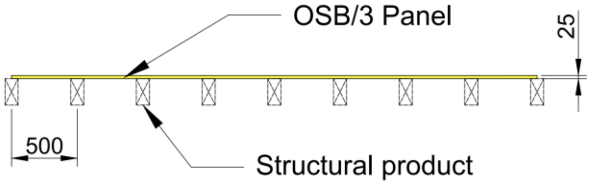

Figure 28 - Side view of residential floor [mm]

4.4.2.3 **Structural analysis**

The structural analysis was made based on the models currently used in the fields of the Strength of Materials and Theory of Structures. The same simplifications were assumed for the design of all structural solutions. For each product, the bending moment and shear values were calculated. Deformations were calculated considering those values. The vibrations were calculated for 1 kN of a pedestrian load. The structural model of each beam is shown in Figure 29.

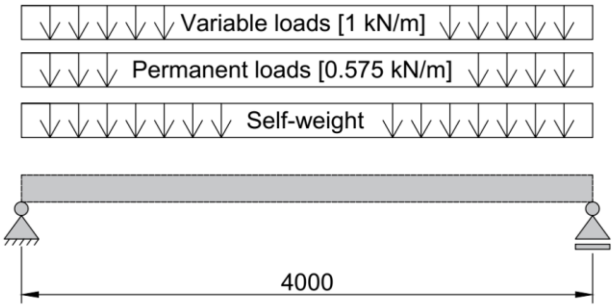

Figure 29 - Structural model [mm]

4.4.2.4 **Design of the structural solutions**

4.4.2.4.1 Design factors

The modification factors applied in structural design were: γ_M, k_{sys}, k_h, k_{mod}, k_{crit}, k_{cr}, and k_{def}. These were the modification factors that influenced the ULS and SLS checks identified in Section 4.4.2.1. The values of the modification factors for each solution are given in Table 31.

Table 31 – Modification factors used for design

	SW	**GLT**	**LVL**	**OSB/3**
γ_m	1.3	1.25	1.2	1.2
k_{sys}	1.1	1.1	1.1	1.0
k_h	1.0	1.1	1.1	1.0
k_{mod}	0.7	0.7	0.7	0.55
k_{crit}	1.0	1.0	1.0	1.0
k_{cr}	0.67	0.67	1.0	1.0
k_{def}	0.6	0.6	0.6	2.25

4.4.2.4.2 Pre-sizing

Pre-sizing was performed based on the average values for short-term deformations given by EN 1995-1-1 (CEN, 2014c), which is the length of the beam divided by 400. The design loads were obtained from the characteristic combination of actions. The self-weight was initially estimated and was adjusted by iterative calculations to the designed cross-section.

The height of the products was estimated based on an empirical rule for pre-sizing of SW structures: the height of the elements can be estimated as the length of the beam (4,000 mm) divided by 20, i.e. 200 mm. The design variable of the rectangular section elements (SW, GLT and LVL) was the width, and the assumed height is 200 mm. The IJ elements were designed based on the width of the flanges. The total height, the width of the web and the height of the flange considered were 200 mm, 10 mm and 45 mm, respectively. The last two dimensions were chosen based on the standard dimensions of the IJ manufacturers. Table 32 shows the dimensions of the cross-sections obtained in pre-sizing.

Table 32 - Cross-sections obtained in pre-sizing of various structural solutions

Structural solutions	**Width [mm]**	**Height [mm]**
C18	92	200
C24	75	200
C30	69	200
C35	63	200
C40	59	200
D24	84	200
D30	77	200
D35	70	200
D40	64	200
GL24h	72	200
GL28h	65	200
Gl32h	58	200
LVL	60	200
IJ C24	126	45
IJ LVL	103	45
IJ OSB	10	110

4.4.2.4.3 Compliance checks

The ULS checks were made by determining whether the bending and shear tensions imposed on the products by the actions were lower than their resistance. SLS checks ensured that the long-term deformations and vibrations do not exceed the EC5 limits. The long-term deformation check determined whether the deformations imposed by actions were lower than the length of beams divided by 300 (mean limit value given by EN 1995-1-1 (CEN, 2014c). Vibration checks ensured that the vertical deflection and the unit impulse velocity response caused by a concentrated static force of 1 kN were lower than the values given in figure 7.2 of EN 1995-1-1 (CEN, 2014c). The ULS design stresses and strengths, the SLS deflections and vibrations values and limits of the structural solutions were given in Tables B-1, B-2, B-3, B-4, and B-5 of Annex B. All the pre-sized cross-sections checked the ULS and SLS verifications.

4.4.2.5 Calculation of the volume of structural products

The volume of the products of each structural solution is given in Table 33 and was calculated using the cross-section dimensions given in Table 32. The volume of the OSB panel was the same for all the structural solutions: 0.400 m^3.

Table 33 – Volume of structural products of each structural solution

Structural solutions	Volume [m^3]
C18	0.662
C24	0.540
C30	0.497
C35	0.454
C40	0.425
D24	0.605
D30	0.554
D35	0.504
D40	0.461
GL24h	0.518
GL28h	0.468
GL32h	0.418
LVL	0.432
IJ C24	0.408
IJ LVL	0.334
IJ OSB	0.040

Comparing the volume of various structural products, it can be seen that C18 was the scenario that had the highest volume, followed by D24. GL32h required the lowest volume. For products with the same bending strength (fm=24 MPa), GLT had the lowest volume followed by Softwoods. For I-Joists, the products that used LVL as flange materials had lower impacts than the products that used C24 as flange materials.

4.5 Durability equivalent functional unit

The amount of preservative product required to guarantee the durability of wood elements depends on the choices made for each design variable, i.e. wood species, treatment method, and preservative product. For that reason, a high number of durability design alternatives exists for the same case study. The comparison of the environmental impacts between two or more design alternatives requires the definition of an equivalence between solutions. The aim of this section is to propose a method to define the durability equivalence for durability projects of wood products.

The proposed method defines the durability equivalence as the amount of preservative product necessary to maintain the durability of wood elements under a **use class** exposure, during the **service life** expected. The method has two main steps: i) definition of the use class and of the service life, and ii) calculation of the product treatment's amount.

The construction and/or structural projects shall be analysed before the definition of a durability equivalence. It shall be ensured that the durability design variables that depend on the structural/construction configuration of wood-elements are the same for all durability solutions (e.g. external surface, volume of wood elements, etc.). When different wood species with different strength classes are used, the volume of wood may differ between the solutions. In these situations, the difference in wood volume should be taken into account, when calculating the amount of preservative product.

4.5.1 Definition of durability equivalent unit

4.5.1.1 Use class and service life

The use classes, given in Table 21, are related to the exposure to weather, humidity, ground contact, fresh water, and saltwater. For each use class, the occurrence of biological degradation agents can be identified. Fungi, beetles and marine borers are ubiquitous durability degrading agents in Europe. Termites occur in specific areas, and it must be checked in advance whether the elements are applied in a site susceptible to this type of attack.

There are some preventive construction measures that can be taken during the design process to prevent the attack by biological agents. If the permanence and occurrence of moisture in wood is avoided and the wood elements are installed in a place with ventilation, the probability of fungus occurrence is reduced, while the placing of non-perforating barriers between the wood elements and the ground avoids the occurrence of termites (Jones & Brischke, 2017).

The appearance of a biological agent can be ignored if it is avoided by preventive construction measures. For situations in which it is not possible to ensure the efficiency of constructive solutions during the entire service life, their occurrence must be considered.

The building owner, user and/or designer must define the service life expected for the wood elements. If there is no information, then the information given by Section 2.3 of EN 1990 (CEN, 2011b) shall be considered (e.g. service life of 50 years).

4.5.1.2 **Calculation of preservative products' amount**

The procedure for the determination of the preservative products' amount followed by this method considers wood species, treatment method, type of preservative product and the number of maintenance operations as variables, each detailed below.

4.5.1.2.1 Wood species (natural durability)

The natural durability varies according to the wood species. EN 350 (CEN, 2016b) gives the natural durability for the most common wood species and their applicability to use classes' conditions shall be assessed using EN 460 (CEN, 1994).

According to EN 350 (CEN, 2016b), sapwood and heartwood have different resistance to biological agents. EN 460 (CEN, 1994) indicates that, when the percentage of heartwood/sapwood of a wood element is not known, it shall be assumed that the element is only composed of sapwood. This assumption can be dangerous if it also contains heartwood, since the latter is neither penetrable nor durable to biological agents. Therefore, the amount of heartwood and sapwood shall be quantified, and their durability and treatability shall be identified. After that, the durability of sapwood and heartwood against biological agents (and use class) shall be verified using EN 460 (CEN, 1994).. Sometimes, the durability of heartwood against fungi is expressed as a range of classes (e.g. 3-4). If a preventive construction design is adopted to prevent the fungi occurrence (avoidance of moisture in wood), the most durable class shall be considered.

When the natural durability of the wood element is not adequate to resist biological agents, preservative products are necessary.

4.5.1.2.2 Treatment method (surface and/or pressure-based)

Surface and pressure-based methods are the most common treatment methods used to preserve wood elements (CEN, 2013c). Besides that, some treatment methods based on modification (chemical and thermal) have been developed recently (Bongers *et al.*, 2009). Since relevant information about these methods is limited, namely the use class applicability and the efficacy period, they were not included in this study.

Surface treatment methods provide a physical barrier between the wood element and the environment that protects it against biological and atmospheric degradation agents. The most common surface methods include brushing, spraying and dipping. The minimum amount of product to be applied as a surface treatment is determined in accordance with EN 599-1 (CEN, 2013c). These methods are applicable to UC1, UC2 and UC3.1 classes. Pressure-based methods treat the wood elements with chemicals that are diffused in the cell wall and in the lumen (inside the cell walls) (Ramage *et al.*, 2017b). These methods are applied in autoclave, with pressure, forcing the treatment products to penetrate the wood. There are two major treatment methods: fill lumen process (or Bethell) and fill cell wall process. The former is used when a maximum retention of preservative product is required, while the latter is applied when deep penetrations with low retention of preservative product are deemed.

If wood elements meet the requirements of EN 599-1 (CEN, 2013c), they can be applied in all use classes. Both types of treatments (surface and pressure-based) may be applied in the same wood element to increase its durability.

4.5.1.2.3 Preservative products

Wood preservative treatments can be grouped into: fixed water-based preservatives, such as copper quaternary alkaline or copper azole; oil-type preservatives such as creosote; and light organic solvent preservatives.

The required amount of surface product is expressed in mass (or volume) of preservative product applied per area of the wood element's surface and the required amount of pressure-based treatment product is expressed as mass of preservative product per volume of wood element.

The production, marketing and use of preservative treatments are regulated in the European Union by the Regulation (EU) No. 528/2012 (EU, 2012). Therefore, only products that comply with these rules shall be considered for wood treatment. Information about the authorised products can be found in the European Chemicals Agency (ECHA) platform (ECHA, 2020). The amount of surface and pressure-based products required to ensure the durability of wood elements is given by technical reports also available on the ECHA platform.

4.5.1.2.4 Amount of preservative product

4.5.1.2.4.1. Surface treatment

The amount of surface product needed is calculated by multiplying the surface area of the wood elements by the yield (in kg/m^2) recommended by the technical data sheets, which depends on the use class.

4.5.1.2.4.2. Pressure-based treatment

The retention of penetrating product depends on the physical properties of the wood species. Figure 30 shows a method to determine the amount of preservative product retained in wood elements. It takes into account the wood species' natural durability, impregnability and the amount of heartwood and sapwood. The choice of the preservative treatments' composition (fungicide or biocide) will depend on the biological agents expected during the service life, and such information can be found in the ECHA platform (ECHA, 2020).

EN 350 (CEN, 2016b) categorises the treatability of sapwood and heartwood in a scale from 1 (easily treated) to 4 (extremely difficult to treat). In this study, it was considered that, when the category is equal to or higher than 3, the wood cannot be penetrated. Whenever a range of values for treatability (for example 3-4) is given, the lowest one shall be considered (3). The expected amount of heartwood and sapwood of a wood sample shall be quantified. If such information is not provided by the supplier, it can be estimated according to EN 350 (CEN, 2016b).

At the end of the procedure, there are three possible alternatives: i) natural durability is enough; ii) pressurised methods cannot be applied; and iii) the amount of preservative product can be calculated. The amount of preservative product retained is calculated by multiplying the retention rate (mass of preservative product per volume of wood) required for the use class by the volume of heartwood and/or sapwood (if impregnable). Where pressure-based methods cannot be applied, and if the class of use is lower than four, the use of different wood species or a surface treatment method should be considered.

4.5.1.2.5 Maintenance period

To maintain their preserving properties, the wood products must be subjected to maintenance operations. The preservative product's technical sheets, provided by the manufacturers, indicate the period during which each product has a preservative effect for a given use class. If the maintenance period is not specified by the supplier, the guarantee period given by the producer shall be considered. At the end of that period, the preserving product must be applied again with the same amount (or a different one defined by the producer).

The number of times that a product is applied during the service life of the wood elements should be determined, and the total amount of product shall be calculated. Finally, the durability equivalence is given by the amount of preservative product required to maintain the wood elements exposed to the conditions of a given use class during its service life.

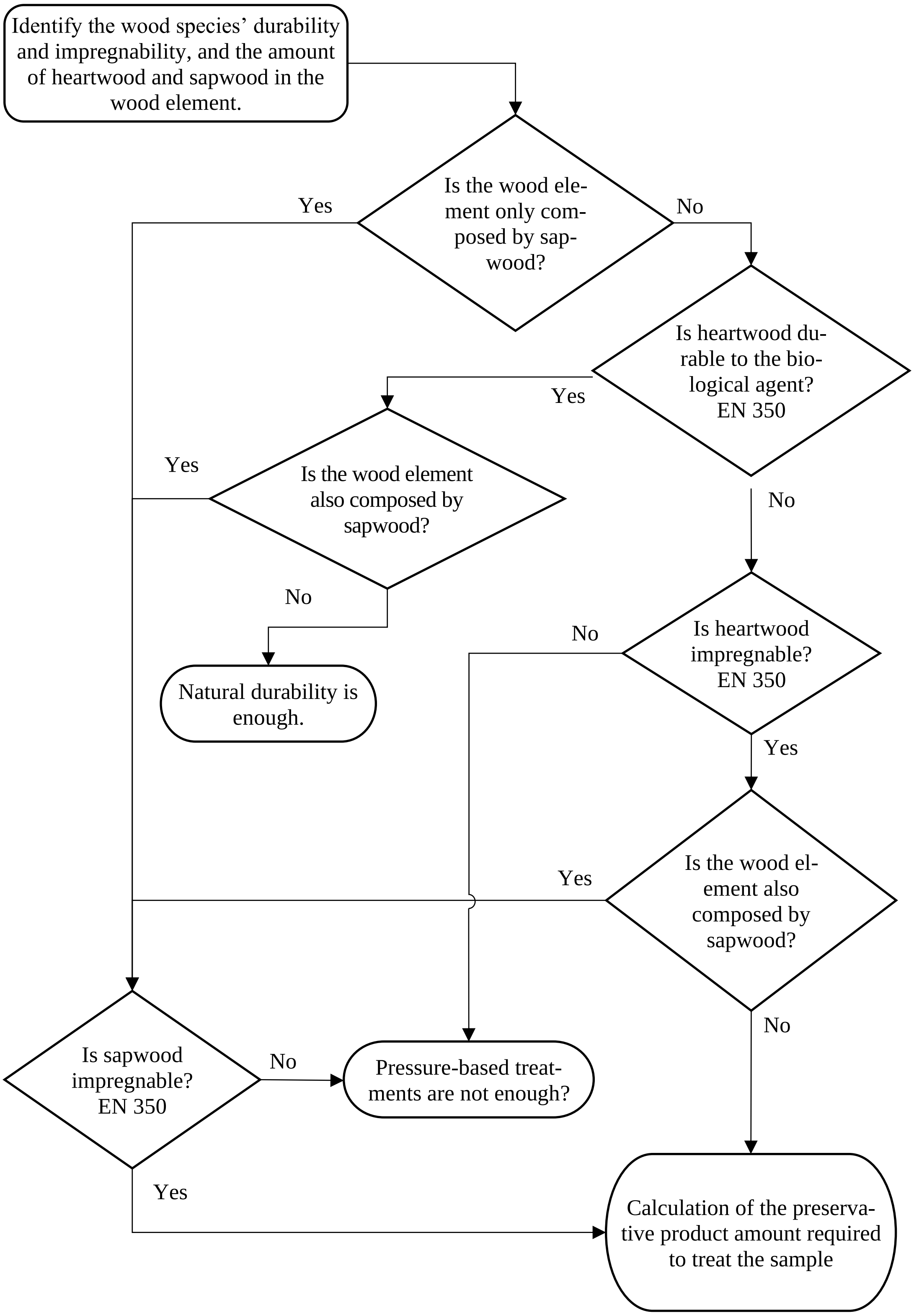

Figure 30 - Flowchart for the calculation of the amount of pressurised product retained in wood elements

4.5.2 Case study – external deck

This section applied the method presented before to calculate and compare the amount of preservative product required to maintain the durability of a specific case study, an external wood deck, whose structural details are depicted in Figure 31. The wood species described in Section 3.3 were considered in the study: Spruce, Scots pine, Maritime pine, Eucalyptus and Cryptomeria. Two preservative products applied by surface (ST) and pressure-based (PT) treatment methods were considered.

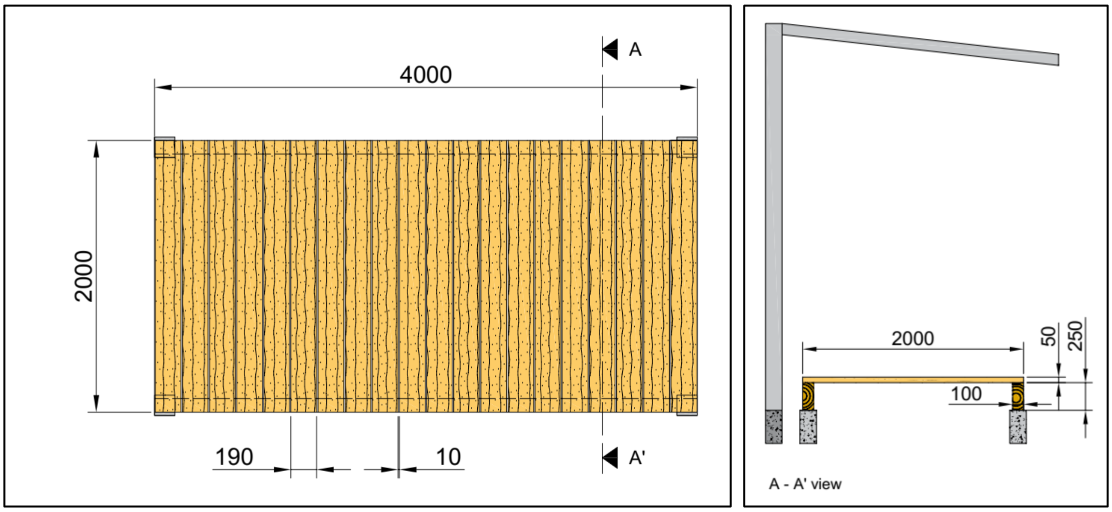

Figure 31 – Plant and side view of the deck solution [mm]

As shown in Figure 31, the deck was to be applied in an external environment under a shading element. The cross-section of the deck elements was previously determined according to EN 1995-1-1 (CEN, 2014c) design guidelines, assuming a C24 strength class, a variable load of 4 kN/m^2 and a permanent load of 0.32 kN/m^2 (self-weight). The designed solution comprised: i) 20 deck boards (190 x 50 mm^2) and ii) two supporting beams (100 x 250 mm^2) resting on four concrete blocks. The configurations of wood elements resulted in 25.60 m^2 of surface area and 0.60 m^3 of volume. Preventive construction measures were adopted such as using a non-perforating element between ground and wood elements (preventing the occurrence of termites) and allowing the ventilation of wood elements (reducing the occurrence of fungi).

4.5.2.1 Use class and service life

As the wood elements were exposed to the weather but water did not accumulate on them, a UC 3.1 exposure was considered. For such use class, according to EN 335 (CEN, 2013a), the occurrence of fungi, beetles and termites was possible; however, the concrete blocks that supported the wood structure prevented the appearance of termites. Therefore, the wood elements were only susceptible to fungi and beetles' attack. A service life of 30 years was defined.

4.5.2.2 Wood species and natural durability

Sapwood and heartwood amount of each species was determined based on "sapwood width" values given by EN 350 (CEN, 2016) for each wood species. For Cryptomeria and Eucalyptus (that have a "small" proportion of sapwood), it is assumed that 40% of the wood element is sapwood and, for Maritime pine (that has a "broad" proportion of sapwood), it is assumed that 60% of the element is sapwood, and for Scots pine (that has a "medium" proportion of sapwood), it is assumed that 50% of the element is sapwood. According to this standard, there is no distinction between the proportion of heartwood and sapwood in Spruce, thus 50% was considered for both. Table 34 summarises the EN 350 (CEN, 2016b) data regarding natural durability and treatability of the selected wood species.

Table 34 - Natural durability and treatability of the selected wood species

	Heartwood durability				**Treatability**	
Wood Species	**Fungi***	**Hylotrupes****	**Anobium****	**Termites****	**Heartwood *****	**Sapwood *****
Cryptomeria	5	D	n/a	S	2-3	1
Spruce	4	S	S	S	3-4	3
Maritime pine	3-4	D	D	S	4	1
Scots pine	3-4	D	D	S	3-4	1
Eucalyptus	5	n/a	n/a	S	3	1

Notes:
***: 3 - moderately durable, 4 - slightly durable, 5 - not durable;**
****: D - durable, S - not durable, n/a - insufficient data available;**
*****: 1 - easy to treat, 2 - moderately easy to treat, 3 - difficult to treat, 4 - extremely difficult to treat.**

Table 34 shows a range of values for Maritime and Scots pines durability against fungi (3-4). As the structural designer adopted a conservative design by separating the deck elements and enabling ventilation of the elements, durability class 3 was considered. Cryptomeria, Spruce and Eucalyptus heartwood are not durable to fungi's attack. Pine species are both durable to beetles. In contrast, Spruce was considered non-durable to xylophage insects. Data available about Cryptomeria and Eucalyptus was insufficient to classify their heartwood durability against beetle's attack. Since sapwood was considered non-durable to any degradable agent, the natural durability of wood species is not enough, requiring the use of preservative treatments in all of them.

4.5.2.3 **Preservative treatments**

ST is a surface treatment applied by brushing. Table 35 shows the composition of this product given by the ECHA report (PPG AC - France SA, 2019). According to the product's technical files, its yield for UC 3.1 is 200 g/m^2 and the preservative efficacy is guaranteed for at least 2 years.

PT is a pressure-based treatment applied by the Bethell method. The ECHA report (Restricted access) (ARCH TIMBER PROTECTION LIMITED, 2018) gives the composition of this product, shown in Table 35. The technical files of this product refer that the amount of preservative to protect wood against fungi and beetles in UC 3 conditions shall be between 8.5 and 18.75 kg/m^3; thus, in this study, the mean value was considered: 13.63 kg/m^3. According to the product's technical files, for UC 3, the efficacy is maintained for at least 15 years.

Table 35 – Chemical composition of ST and PT products

Treatment	Compound common name	CAS number	Content (% w/w)
ST	Cypermethrin	52315-07-8	0.08
	Propiconazole	60207-90-1	0.16
	Tebuconazole	107534-96-3	0.05
	IPBC	55406-53-6	0.05
	Solvent naphtha	-	97.15
PT	Basic copper carbonate	12069-69-1	14.57
	Tebuconazole	107534-96-3	0.16
	DDA Chloride	7173-51-5	0.5
	DDA Carbonate	894406-76-9	0.5
	Propiconazole	262-104-4	0.16
	Monoethanolamine	141-43-5	26.91
	Confidential compound	Confidential data	57.2

4.5.2.4 **Quantification of the amount of preservative products**

The amount of surface treatment was calculated by multiplying the yield by the total external surface of the wood element. As the yield does not depend on the wood species and type of wood (sapwood or heartwood), and the wood surface was the same for all species (C24 strength class), the amount of surface treatment spent was the same for all wood species. Therefore, the amount of surface preservative product was 5.12 kg (25.60 m^2 (external surface) x 200 g/m^2 (yield)) per application.

The results obtained from the application of Figure 30 procedure (amount of pressure-based preservative product retained in wood calculated for each wood species, including both sapwood and heartwood) are presented in Table 36.

Table 36 – Calculation of the amount of pressure-based preservative product retained in wood species

Wood specie	Heartwood		Sapwood	Pressurised preservative product retained [kg/m^3]		
	Durable?	Impregnable?	Impregnable?	Heartwood	Sapwood	Total
Cryptomeria	No	Yes	Yes	8.18	5.45	13.63
Spruce	No	No	No	-	-	-
Maritime pine	Yes	No	Yes	0	8.18	8.18
Scots pine	Yes	No	Yes	0	6.81	6.81
Eucalyptus	No	No	Yes	-	-	-

As the heartwood of Spruce and Eucalyptus are neither durable nor impregnable, they cannot be applied in UC 3.1, even if treated by pressure-based methods. Despite this, Spruce sapwood is also not impregnable, which invalidates the pressure-based treatment for this species. Cryptomeria, Maritime pine and Scots pine retained an amount of 13.63 kg/m^3, 8.18 kg/m^3 and 6.81 kg/m^3 of preservative treatment in UC 3.1 applications, respectively. Considering the total volume of wood (0.60 m^3), Cryptomeria, Maritime pine and Scots pine elements retained a total of 8.18 kg, 4.91 kg and 4.09 kg of PT product, respectively.

4.5.2.5 Service life

As the expected service life is 30 years and the efficiency of the surface preservative product is 2 years, the product will be reapplied 25 times during the service life of wood elements. For the pressure-based preservative treatment, the estimated service life is 15 years. As the re-application of pressure-based preservative products requires the dismantling of the constructive solution, the maintenance operations of these elements usually involve substituting the older wood elements with newly treated elements. Therefore, the total amount of pressure-based product is obtained by quadrupling the first application product’s amount. Table 36 gives the total amount of preservative products applied during the service life.

Table 37 - Total amount of preservative products applied during the service life of deck

Wood species	ST [kg]		PT [kg]	
	First application	30 years of use	First application	30 years of use
Cryptomeria	5.12	76.8	8.18	16.36
Spruce			-	-
Maritime pine			4.91	9.81
Scots pine			4.09	8.18
Eucalyptus			-	-

4.6 Conclusions

This chapter proposed two methods for comparison of structural sawnwood, two methods for comparison of structural products, one method for comparison of structural solutions and one method for comparison of durability scenarios.

At the sawnwood level, the estimation of strength classes was made through the visual and mechanical grading methodologies. The visual based methodology consists of the collection of data from datasets (mean modulus of elasticity, density, and strength class or mechanical properties (if provided). The data collected were used to estimate the strength classes through the methodology given by EN 1912 (CEN, 2012b). For wood species and country of origin studied, the strength classes identified were C30 for Maritime pine scenario, D40 for Eucalyptus, C14 for Cryptomeria and C24 for the remaining scenarios.

The mechanical grading methodology consists of the identification of combinations of strength classes and the yield of wood batch that corresponds to each strength class. In this study, the mechanical grading methodology was applied to Maritime pine sawnwood from Portugal, and four grades were identified: C35 (81.9%), C24 (6.9%), C18 (6.6%) and 4.6% of wood elements were rejected.

At the product level, two equivalent units were defined based on bending strength and modulus of elasticity of products for comparison of structural and environmental performance. The equivalent units calculate the volume of structural products required to fulfil the structural requirements imposed by a “unit” case study. For both equivalent units, Cryptomeria was the scenario that had the highest volume and Eucalyptus was the scenario that had the lowest volume.

At the building level, this study proposed two methodologies for definition of an equivalent functional unit for structural comparisons and an equivalent functional unit for durability comparisons. The methodology proposed for structural comparison consists of five steps: definition of functional equivalence, definition of structural solutions, structural analysis, design of structural solutions and calculation of the volume of structural products. Various structural solutions that varied the structural products and strength classes were compared: softwoods (C18, C24, C30, C35 and C40), hardwoods (D24, D30, D35 and D40), GLT (GL24h, GL28h and GL32h), LVL, IJ made with LVL and IJ made with C24. GL32h was the scenario that required the lowest amount of volume, and C18 required the highest amount of volume. For each product, the increase of bending strength of products reduced the amount of structural volume.

For durability scenarios, the equivalence was defined through the identification of use class and service life, selection of wood species and preservative treatments, quantification of preservative products amount applied during the service life of wooden elements. This study compared the amount of two types of preservative products (surface and penetrating) and five wood species (Maritime pine, Cryptomeria, Eucalyptus, Scots pine and Norway spruce). The methodology followed identified that spruce and Eucalyptus were not suitable for penetrating treatments. On the other hand, Cryptomeria required the highest amount of penetrating treatment and Scots pine required the lowest amount of penetrating treatment.

5 DEFINITION OF CASE STUDIES

5.1 General

As stated in Section 2, the definition of goal and scope must consider the functional unit and/or declared unit, system boundary, allocation procedures, cut-off criterion, data collection procedure, data quality requirements, assumptions and limitations of the study. The description of how these issues are addressed is presented below.

This study applied the LCA methodology at three assessment levels: i) forest management, ii) production of structural products, and iii) building solutions. The goal and scope varied for each level and are given below for each one. The functional units are detailed for each level in Section 5.2, and the system boundaries are described in detail for each life cycle stage in Section 5.3.

The goals of this study were: i) performing LCA studies of structural timber products at various levels of their production, ii) the comparison of environmental impacts for various scenarios, iii) the benchmarking of Portuguese structural sawnwood industries, and iv) the identification of environmental "*hotspots*" during the life cycle of these products. This study intended to be representative of: the last decade (from 2010 to 2020); the European and Portuguese production scenarios; and the typical technology used in these geographical places during these years.

5.1.1 Case studies

The case studies were defined for each assessment level. At the forest management level, the case studies covered the production of roundwood coming from forests with various management scenarios (given in Section 3.3). The aim at this level was to quantify and compare the environmental performance of various European forest management scenarios. Those scenarios were:

- Planted Maritime pine from Portuguese forests,
- Seeded Maritime pine from Portuguese forests,
- Naturally regenerated Maritime pine from Portuguese forests,
- Planted Cryptomeria from Azorean forests,
- Planted Eucalyptus from Portuguese forests,
- Planted Spruce from Sweden forests,
- Planted Scots pine from Sweden forests,

- Planted Spruce from German forests,
- Planted Scots pine from German forests.

At the structural products level, this study considered the production of various structural wood-based products, such as SW, GLT, and LVL. At this stage, this study intended to quantify and compare their environmental performance. The comparison was made through the equivalent functional scenario defined in Section 4.2.1 that takes into account the visual grading. The list of products analysed is given bellow:

- Maritime pine sawnwood from Portugal,
- Eucalyptus sawnwood from Portugal,
- Cryptomeria sawnwood from Portugal,
- Spruce sawnwood from Germany,
- Spruce sawnwood from Sweden,
- Scots pine sawnwood from Germany,
- Scots pine sawnwood from Sweden,
- Glulam produced in Europe,
- LVL produced in Europe.

At the building level, this LCA study analysed two case studies: i) a residential interior floor and ii) an exterior deck. The aim of the residential interior floor case study was to identify which combination of structural products and strength classes leads to the highest environmental performance. For this reason, the functional unit was given by the minimum volume of structural products complying with the structural requirements and rules given by EN 1990 (CEN, 2011b) and EN 1995-1-1 (CEN, 2014c). To ensure the equivalence between various scenarios, the procedure for the calculation of this volume followed the procedure of functional equivalence definition given in Section 4.4. As this case study was applied under the controlled conditions of Service Class 1 and Use class 1, the durability aspects of structural products were not taken into account in the definition of its scenarios (for example, in the wood species choice). The structural scenarios included different structural products, namely:

- Maritime pine sawnwood from Portugal,
- Eucalyptus sawnwood from Portugal,
- Cryptomeria sawnwood from Portugal,
- Spruce sawnwood from Germany,
- Spruce sawnwood from Sweden,
- Scots pine sawnwood from Germany,
- Scots pine sawnwood from Sweden,
- Glulam produced in Europe,
- LVL produced in Europe,

- I-Joists produced in Europe with two different flanges' materials: C24 and LVL. The web of both is made of OSB/3.

The strength classes of sawnwood products were determined by the visual grading methodology, based on the methodology proposed in Section 4.2.1 of this study. A strength class of GL24h was considered for GLT products and the strength and stiffness properties of KertoS were considered for LVL products and flanges of I-Joists.

The exterior deck case study intended to identify which combination of wood specie and application of preservative treatment method has better environmental performance. The functional unit in this case study was given by the minimum amount of preservative product necessary to maintain the durability of wood elements for a UC3.1, for 30 years. The calculation of the preservative product amount for various scenarios followed the functional equivalence method given in Section 4.5. This case study did not include the structural variables, such as strength classes and structural configurations. The scenarios modelled are given below:

- Cryptomeria sawnwood with a pressure-based treatment,
- Maritime pine sawnwood with a pressure-based treatment,
- Scots pine sawnwood with a pressure-based treatment,
- Cryptomeria sawnwood with a surface treatment,
- Spruce sawnwood with a surface treatment,
- Eucalyptus sawnwood with a surface treatment,
- Maritime pine sawnwood with a surface treatment,
- Scots pine sawnwood with a surface treatment.

5.1.2 Data collection methodologies

The inventory data for the various products were acquired from two sources: i) LCA databases, and ii) visits and enquiries to companies. The LCA database used in this study was Ecoinvent 3.6 (Wernet *et al.*, 2016). Ecoinvent database was used to model the forest management operations, the transportation processes, the production of structural and durability products and the treatment processes. In addition, this database was also used to model the background processes of the data collected in companies. The data collected in companies were used to model the forestry processes for roundwood production of Maritime pine, Eucalyptus and Cryptomeria, and the sawmilling operations of Maritime pine.

The data collected were also used to identify the industry practices that lead to the improvement of the environmental and economic performance of products (benchmarking). Therefore, whenever possible, simulations were made with data collected from companies' inquiries and LCA databases. Among others, these simulations corresponded to sensitivity analyses of distinct aspects, such as allocation (massic or economic), company decisions influencing system boundaries and LCI (e.g. fuels consumption). Those sensitivity analyses are presented and discussed in Chapter 8. The methodologies followed for the collection of data followed the rules established for EPDs through the ISO and CEN standards.

5.1.3 Cut-off criterion and Allocation procedures

Due to the specificities of this study, all available data were collected, not following a specific cut-off rule. Nevertheless, the flows that were identified by companies as residual or non-prejudicial to the environment were not quantified in the LCI. The allocation method (e.g. massic or economic) was defined for each product and/or corresponding production processes, according to the recommendations of EN 15804 (CEN, 2012a). The allocation procedure followed in the majority of the processes, modelled through visits and enquiries to producing companies, was based on physical properties (such as volume). EN 15804+A2 (CEN, 2019) stated that when the difference between the physical output flows of co-products is higher then 25%, then an economical allocation must be used. Pargana et al. (2014) stated that this type of allocation leads to final results that do not regard the inherent physical relationships between the products and these results cannot be compared with the LCA results available on EPDs and LCA databases because the latter are usually reached using allocation procedures based on physical relations. For this reason, this study followed volumetric based allocation procedures. In some cases, different allocation methods were used, and the corresponding results were compared. This comparison was performed in Section 8.

5.1.4 Data quality requirements

Data quality requirements were considered in the LCI of each production company inventoried in order to obtain the same representativeness defined by the goal and scope of the study. The requirements for data quality followed in this study were those requested by ISO 14044 (ISO, 2006c), which are described below:

- Time-related coverage: the data collected must be representative of a period equal or higher than one year. The data collected were representative of one year or more than one year, during the last decade (from 2010 to 2020),
- Geographical coverage: the data collected were representative of the European region. For some cases, the geographical coverage was restrained to country-specific data. Whenever this occurred, the geographical coverage was indicated during the LCI procedures description,

- Technology coverage: the data collected in LCA databases covered typical European technology. The data collected through inquiries cover the specific technology of the companies inventoried,
- Precision: the data collected were not characterised in terms of variance,
- Completeness: the site-specific data collected in this study were representative of the totality of the company flows,
- Consistency: the same consistency requirements were followed during the collection and modulation of data, namely the requirements given by ISO 14040 and ISO 14044,
- Reproducibility: the data collection procedure used a form that was developed based on the example given in Annex A of ISO 14044 (ISO, 2006c). The form was filled by a technician of the company for each unit process identified by the author, during visits to the production company. Although the companies requested a confidential treatment of the data, the author considers that the methodology followed and the data presented in this Thesis ensure the reproducibility of data and results,
- Uncertainty of the information and missing data: whenever the data was not available or was identified as uncertain, the authors noted down and considered it in the LCA analysis phases.

5.2 **Definition of functional units**

The functional units of this study varied with the levels assessed (forest management, production of structural products, and building solutions). At the forest management level, the functional unit was: 1 m^3 of roundwood under bark, at the forest road (Figure 32). The functional unit for the production of structural products was: 1 m^3 of product at the gate of the production factory (for SW, GLT and LVL) and 1 linear meter of product at the gate of the production factory (for IJ).

Figure 32 – Maritime pine roundwood under bark at the forest road

For building solutions, the functional unit of the case study of the residential floor was the minimum volume of wood and/or wood-based structural product that complies with the structural requirements given by European standards for the design of an interior floor (4x4 m^2) for 50 years. The functional unit of the exterior deck was the minimum amount of wood and preservative product necessary to maintain the durability of wood elements under a Use Class 3.1 exposure for 30 years.

5.3 **System boundary and data collection**

This section details the system boundary of each product and the data collection methodologies followed. According to the nomenclature given by Figure 1 of EN 15804+A2 (CEN, 2019), the system boundaries of this study are from “cradle-to-grave and module D”. These boundaries include: the production stage (A1-A3), the construction stage (A4-A5), the use stage (B1-B7), the end-of-life stage (C1-C4), and a stage that takes into account the benefits and loads beyond the system boundary (Module D). The operations modelled in each stage and the data collection methodologies followed are described next. The operations performed during each stage were identified based on the literature review performed in Section 2.4, the Ecoinvent inventory reports (Wernet *et al.*, 2016), and the companies’ inquiries performed and filled during this study.

The system boundaries varied for each level of assessment. Regarding the “forest management” level, the system boundaries cover the operations performed during stage A1. The system boundaries of the “production of structural products” level covers the operations performed during stages A1, A2 and A3. The system boundary of “building solutions” covers all the operations performed during the life cycle of products, including module D. These allocations are summarized in Table 38.

Table 38 – Operations considered for each level of assessment

Level of assessment	**A1**	**A2**	**A3**	**A4-A5**	**B1-B7**	**C1-C4**	**D**
Forest management	X						
Production of structural products	X	X	X				
Building solutions	X	X	X	X	X	X	X

5.3.1 Production Stage (A1-A3)

5.3.1.1 **Structural wooden products**

The production stage of wooden products begins in the forest, with the tree’s growth, and ends at the gate of the structural products’ factory. This stage was divided into: forest operations (stage A1), transport from forest to production factory (stage A2), and production of structural products (stage A3).

5.3.1.1.1 Forest operations (Stage A1)

Based on the literature review, this study divided stage A1 into three sub-stages: site preparation (Stage 1.1), stand establishment and tending (Stage 1.2) and logging operations (Stage 1.3). The operations performed during each sub-stage depend on the forest management plan of producers for the forest land. The data used to model stage A1 was obtained through companies' inquiries and databases' processes. The data collection of this stage considered that the declared unit was 1 m^3 of roundwood located at the forest road.

The various forest scenarios modelled varied the wood species, country of origin, and type of plantation. Maritime pine, Cryptomeria, and Eucalyptus from Portugal, and Spruce and Scots pine from Germany and Sweden, were considered. Three types of plantations are modelled: through seeds (by throwing tree seeds to the land), through plants (by planting seedlings provided by a plant nursery), and through natural regeneration (by expecting the natural regenerating of trees).

In the scope of this study, company inquiries were conducted to collect data used to model the forest scenarios, such as operations performed at each sub-stage, yield of operations (inputs and outputs), productivity and yield of forest scenarios, and lifespan of forest management scenarios. These inquiries were used to model the following Portuguese forest scenarios: Maritime pine seeded (MP_Seed_PT), Maritime pine planted (MP_Plant_PT), Maritime pine natural regeneration (MP_NR_PT), Eucalyptus planted (Euc_Plant_PT), and Cryptomeria planted (Cryt_Plant_PT). The Ecoinvent database was used to model the following forest scenarios: Swedish Spruce planted (Sprc_Plant_SE), Swedish Scots pine planted (SPine_Plant_SE), German Spruce planted (SPrc_Plant_DE), and German Scots pine planted (SPine_Plant_DE). The data collected are presented in Chapter 6.

The system boundary of German representative processes given by the Ecoinvent database (SPrc_Plant_DE and SPine_Plant_DE) covered: stand establishment, tending and harvesting. The system boundary of Swedish products included in the same database (SPrc_Plant_SE and SPine_Plant_SE) covered: site preparation, stand establishment and tending, and harvesting. The scenarios of Portuguese planted trees (MP_Plant_PT, Euc_Plant_PT and Cryt_Plant_PT) and seeded trees (MP_Seed_PT) included: site preparation, stand establishment and tending and harvesting. The scenario of Portuguese natural regenerated trees covered: stand establishment and tending and harvesting. Natural regeneration process (MP_NR_PT) excluded the site preparation operations.

For Portuguese scenarios, the operations modelled were recommended by a forest certification company (FSC certification) for forest management. For Swedish and Germany's scenarios, the operations were those identified by the Ecoinvent 3.6 report (Wernet *et al.*, 2016).

Swedish's forest management scenarios for Spruce and Pinus Sylvestris covered the following operations:

- Site preparation: soil scarification with harrows, mechanical site preparation with forwarder, and construction and maintenance of forest roads,
- Stand establishment and tending: seedling production (from heated and unheated greenhouses), planting with tractor, tending with brush cutter, young growth tending with brush cutter, selective cleaning with power saw, and systematic cleaning with crusher on tractor,
- Logging operations: thinning and final harvesting (power saw with tractor and/or harvester with forwarder).

Germany's forest management scenarios for Spruce and Pinus Sylvestris (with natural regeneration) cover the following operations:

- Stand establishment and tending: stand establishment with tractor, tending with brush cutter, young growth tending with brush cutter, selective cleaning with power saw, systematic cleaning with crusher on tractor; and fertilising with helicopter,
- Logging operations: thinning and final harvesting (power saw with tractor and/or harvester with forwarder).

The Portuguese’s scenarios for Maritime pine seeded, Maritime pine planted and Eucalyptus planted covers the following operations:

- Site preparation: harrowing with disk harrow, ploughing, subsoiling with subsoiler plow, and road construction and management,
- Stand establishment and tending: fertilising, seedling production (from unheated greenhouses – for planted scenario), manual planting (Figure 33-a), mechanical weed control with forwarder, thinning and pruning with power saw, and forwarding of thinned logs with forwarder (Figure 33-b),
- Logging operations: final harvesting with harvester, extraction with tractor and forwarding with forwarder (Figure 34).

The Portuguese’ scenario for Maritime pine naturally generated covered the operations described previously, excluding site preparation. In addition, the Cryptomeria scenario covered the same operations, but excluding fertilising.

Figure 33 – a) Manual planting operation; b) Forwarding of thinned logs with forwarder

Figure 34 – Forwarding of roundwood with forwarder

The productivity of German and Swedish forest scenarios was given by the Ecoinvent 3 support documents (Wernet *et al.*, 2016). The productivity of Portuguese scenarios was given by a forest management company. According to this company, the values considered are representative of the Portuguese mean productivity for each scenario. The productivity considered for Maritime pine and Eucalyptus stands were slightly higher than the literature review, which was a consequence of the consideration of fertilising operations performed during the trees' growth. According to EN 15804+A2 (CEN, 2019), infrastructure construction and maintenance processes should be excluded from system boundaries. However, in the German and Swedish Ecoinvent processes it is not possible to exclude infrastructure operations and for that reason these processes have been considered in all scenarios.

The operations performed during the forest management and the year in which each operation is carried out for Portuguese scenarios are presented in Table 39, Table 40, Table

41, Table 42, and Table 43 for MP_Seed_PT, MP_NR_PT, MP_Plant_PT, Euc_Plant_PT and Cryp_Plant_PT, repectively. The system boundaries of each scenario are schematized in Figure 35, Figure 36, Figure 37, Figure 38 for MP_Plant_PT and MP_Seed_PT, MP_NR_PT, Euc_Plant_PT and Cryp_Plant_PT, respectively.

Table 39 – Forest operations performed during the seedling management scenario of Maritime pine and year of operation

MP_Seed_PT	Operation	Year of operation
Site preparation	Harrowing with disk harrow	0
	Ploughing	0
	Subsoiling with subsoiler plow	0
	Road construction	0
	Road maintenance	5, 10, 15, 20, 25, 30, 35, 40, 45
Stand establishment and tending	Seedling	0
	P Fertilising	0
	N Fertilising	10, 15
	Mechanical weed control with forwarder	10, 15, 25
	Thinning and pruning with power saw	10, 15, 25, 32.5
	Forwarding of thinned logs with forwarder	10, 15, 25, 32.5
Logging operations	Final harvesting with harvester	45
	Extraction with tractor	45
	Forwarding with forwarder	45

Table 40 - Forest operations performed during the natural regeneration management scenario of Maritime pine and year of operation

MP_NR_PT	Operation	Year of operation
Site preparation	Ploughing	4
	Road construction	5
	Road maintenance	10, 15, 20, 25, 30, 35, 40, 45,
Stand establishment and tending	N Fertilising	7.5, 15
	Mechanical weed control with forwarder	7.5, 15, 25
	Thinning and pruning with power saw	7.5, 15, 25, 32.5
	Forwarding of thinned logs with forwarder	7.5, 15, 25, 32.5
Logging operations	Final harvesting with harvester	45
	Extraction with tractor	45
	Forwarding with forwarder	45

Table 41 - Forest operations performed during the planting management scenario of Maritime pine and year of operation

MP_Plant_PT	Operation	Year of operation
Site preparation	Harrowing with disk harrow	0
	Ploughing	0
	Subsoiling with subsoiler plow	0
	Road construction	0
	Road maintenance	5, 10, 15, 20, 25, 30, 35, 40, 45
Stand establishment and tending	Seedling	0
	P fertilising	0
	N fertilising	15, 25
	Mechanical weed control with forwarder	8, 9, 10, 22
	Thinning and pruning with power saw	7.5, 15, 25, 32.5
	Forwarding of thinned logs with forwarder	7.5, 15, 25, 32.5
Logging operations	Final harvesting with harvester	45
	Extraction with tractor	45
	Forwarding with forwarder	45

Table 42 - Forest operations performed during the planting management scenario of Eucalyptus and year of operation

Euc_plant_pt	Operation	Year of operation
Site preparation	Harrowing with disk harrow	0
	Ploughing	0
	Subsoiling with subsoiler plow	0
	Road construction	0
	Road maintenance	5, 10, 15, 20, 25, 30, 35, 40, 45
Stand establishment and tending	Seedling	0
	N fertilising	0
	P fertilising	15, 25
	Mechanical weed control with forwarder	8, 9, 10, 22
	Thinning and pruning with power saw	7.5, 15, 25, 32.5
	Forwarding of thinned logs with forwarder	7.5, 15, 25, 32.5
Logging operations	Final harvesting with harvester	45
	Extraction with tractor	45
	Forwarding with forwarder	45

Table 43 - Forest operations performed during the planting management scenario of Cryptomeria and year of operation

Cryp_plant_pt	**Operation**	**Year of operation**
Site preparation	Harrowing with disk harrow	0
	Ploughing	0
	Subsoiling with subsoiler plow	0
	Road construction	0
	Road maintenance	5, 10, 15, 20, 25, 30, 35, 40, 45
Stand establishment and tending	Seedling	0
	Mechanical weed control with forwarder	1, 2, 3, 4
	Thinning and pruning with power saw	5, 10, 15
	Forwarding of thinned logs with forwarder	5, 10, 15
Logging operations	Final harvesting with harvester	45
	Extraction with tractor	45
	Forwarding with forwarder	45

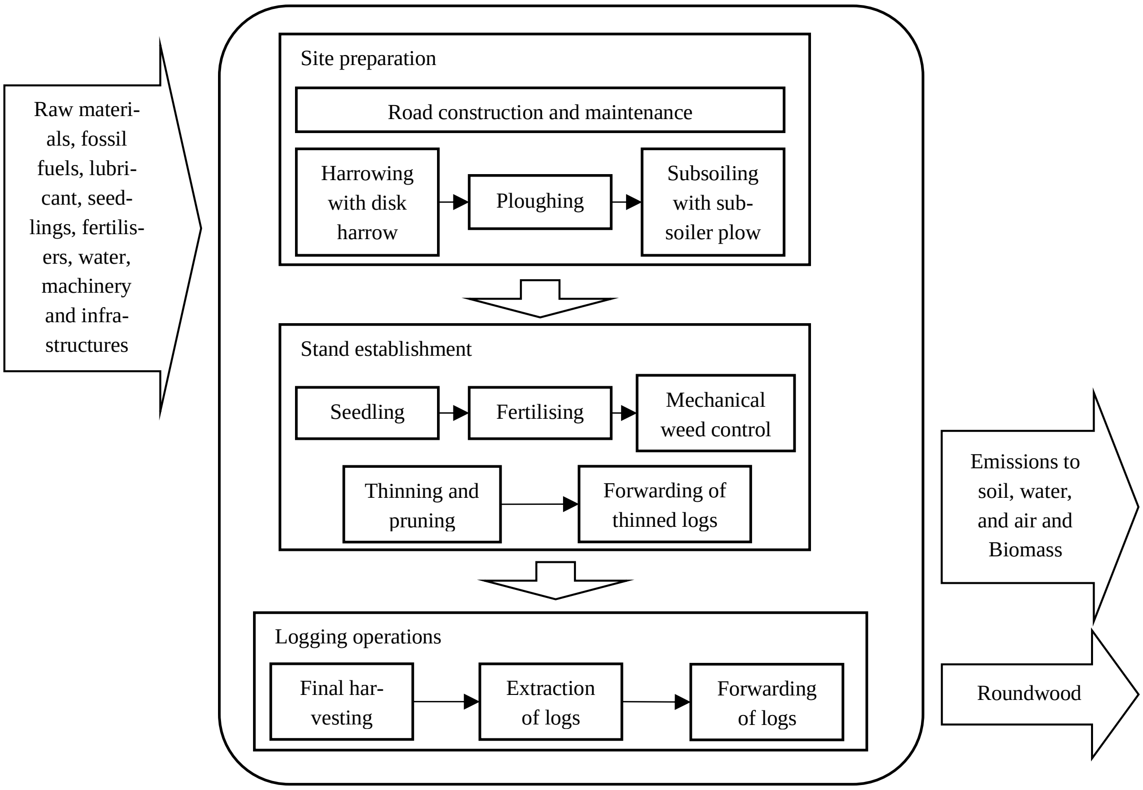

Figure 35 – System boundary of MP_Plant_PT and MP_Seed_PT sawnwood production scenarios

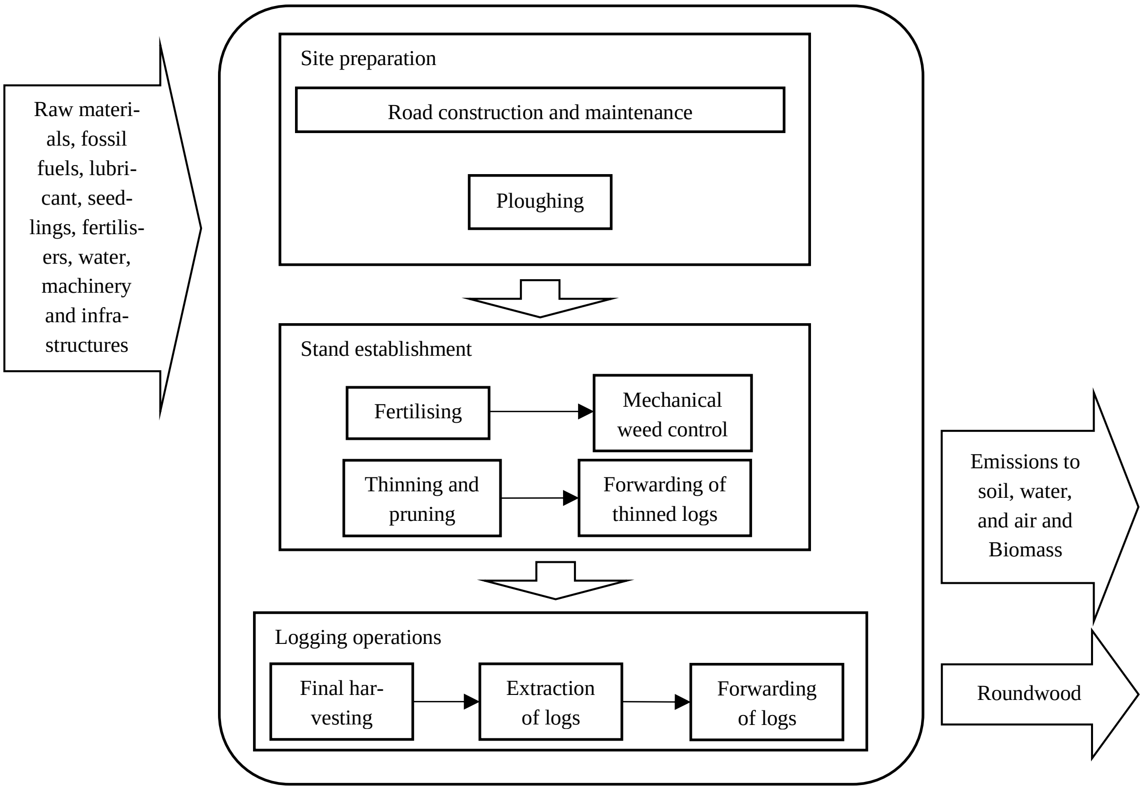

Figure 36 – System boundary of MP_NR_PT sawnwood production scenario

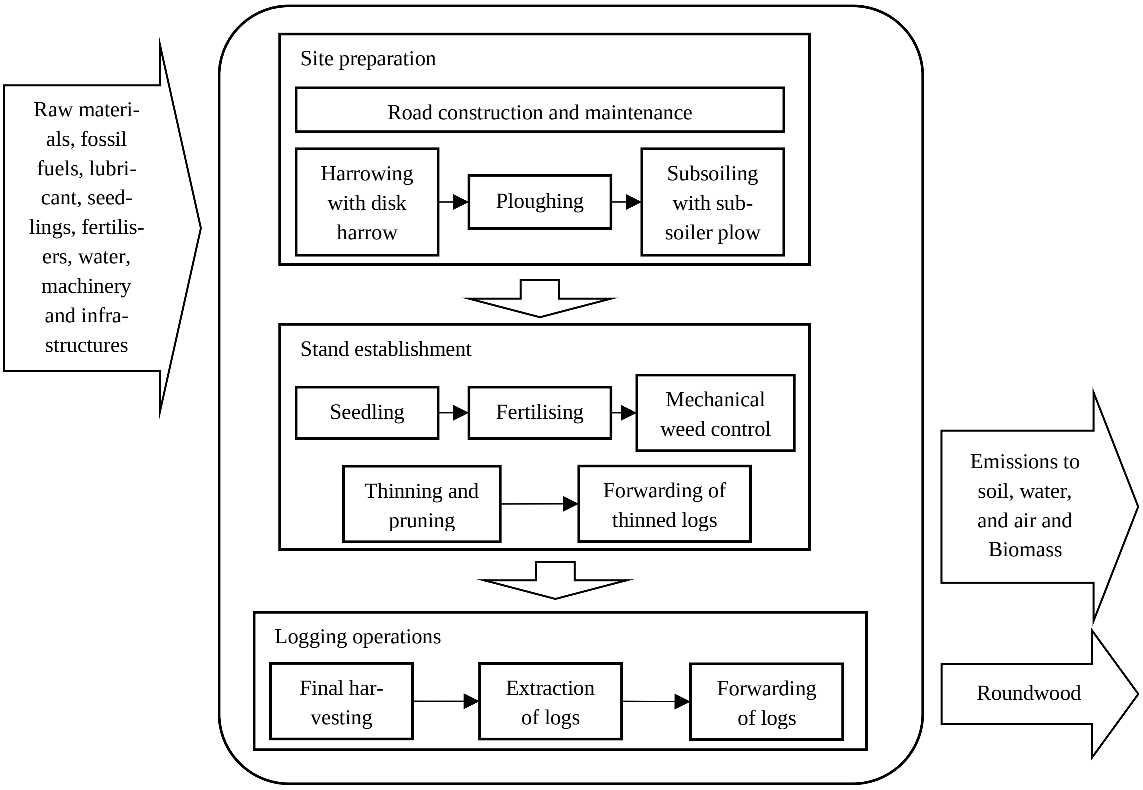

Figure 37 – System boundary of Euc_Plant_PT sawnwood production scenario

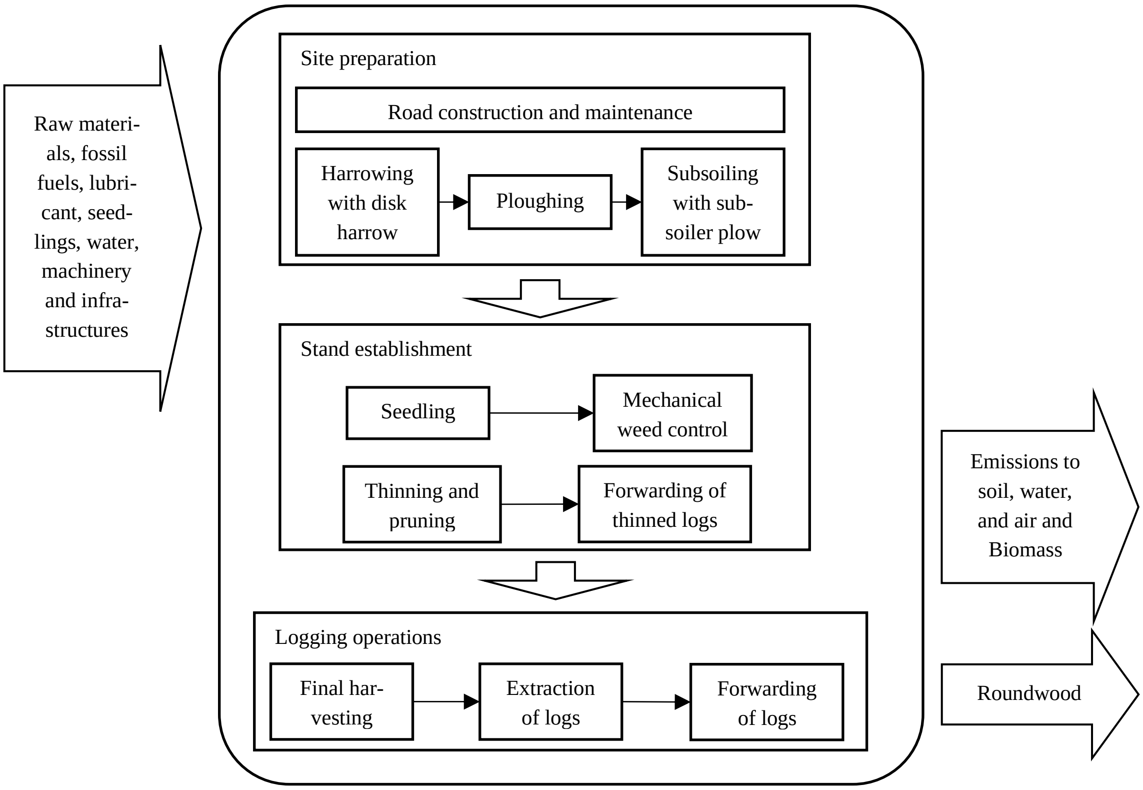

Figure 38 – System boundary of Cryp_Plant_PT sawnwood production scenario

5.3.1.1.2 <u>Transport to the sawmill (Stage A2)</u>

The roundwood, after being placed at the forest roadside, is transported to the sawmill and/or other wood processing industries. These transportation processes are usually performed with cargo trucks equipped, or not, with cranes (Figure 39-a). For the cases in which the transportation is made by sea (for example, Cryptomeria from the Azores Islands), this transportation is made by container ships (Figure 39-b).

Figure 39 – a) Transportation of roundwood from forest to the sawmill by cargo truck, b) Transportation of roundwood by container ships.

The transport operations of Sprc_Plant_SW, SPine_Plant_SW, SPrc_Plant_DE, and SPine_Plant_DE were modelled by using the Ecoinvent database (Wernet *et al.*, 2016) processes. Those processes were modelled considering the technological representativeness of corresponding countries. The type of transport and mean distances of MP_Seed_PT, MP_Plant_PT, MP_NR_PT, Euc_Plant_PT, and Cryt_Plant_PT scenarios were modelled through company inquiries.

5.3.1.1.3 Production of construction products (Stage A3)

According to the goal of this study, the production of Sawnwood, Glulam, LVL, OSB and I-Joist was modelled in stage A3. The production of Sawnwood was modelled through companies' inquiries and Ecoinvent database processes. Due to the lack of production companies in the Portuguese industrial scene, the production of Glulam, LVL, OSB and I-Joist was modelled through Ecoinvent database processes. The scenarios modelled were: Maritime pine sawnwood produced in Portugal (SW_MP_PT), Eucalyptus sawnwood produced in Portugal (SW_Euc_PT), Cryptomeria sawnwood produced in Portugal (SW_Cryp_PT), Scots pine sawnwood produced in Sweden (SW_SPine_SE), Spruce sawnwood produced in Sweden (SW_SPrc_SE), Scots pine sawnwood produced in Germany (SW_SPine_DE), Spruce sawnwood produced in Germany (SW_SPrc_DE), Glulam (European mean) (GLT), LVL (European mean) (LVL), OSB (European mean) (OSB), I-Joist (European mean) with C24 wood in flanges (IJ_C24), and I-Joist (European mean) with LVL in flanges (IJ_LVL). The system boundary and data collection method followed in each scenario are described below. The inputs and outputs of each scenario described are presented in Section 6.2.3.

The SW_MP_PT scenario was modelled through inquiries to a Maritime pine sawnwood production company. The study analysed a company located in Sertã (Centro region of Portugal) and the technology was representative of the national practice. The data was representative of the year 2016 (avoiding the influence of wildfires in the Centro region during the year 2017). The system boundary of this scenario covered: unloading of roundwood, debarking, sawing, burning of wooden chips for heat production, drying, marking, storage, packaging and loading of sawnwood into trucks. The inputs of the system boundary considered were roundwood, electricity, water, diesel, lubricant, and packaging film. The main outputs of the system boundary were sawnwood, sawdust, wood chips and bark. Some of the wood chips co-produced are used by the boiler plant to heat the drying oven. The emissions of the boiler were also considered in the system boundary. The wastes generated during the sawmilling of Maritime pine sawnwood, such as mineral oil waste and hazardous waste, were also taken into account. The system boundary of the SW_MP_PT scenario is shown in Figure 40.

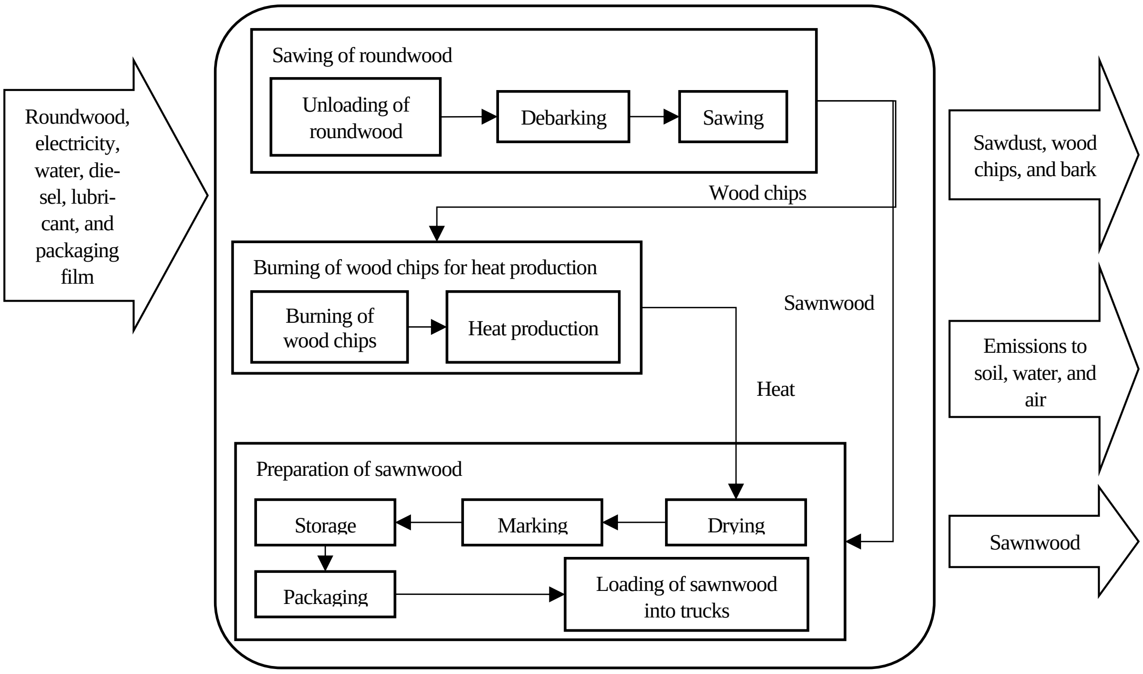

Figure 40 – System boundary of SW_MP_PT sawnwood production

The main product of the majority of Portuguese sawmills is Maritime pine sawnwood. Portuguese sawnwood from other species is produced in the same sawmills that produce Maritime pine sawnwood. For that reason, it was difficult to model a scenario for one specific wood specie, such as Eucalyptus and Cryptomeria. Those species were therefore modelled based on European production processes available at the Ecoinvent database (Wernet *et al.*, 2016).

The SW_Euc_PT, SW_Cryp_PT, SW_SPine_SE, SW_ SPrc _SE, SW_SPine_DE, SW_ SPrc _DE scenarios were modelled based on a Ecoinvent process, representative of the global production of sawnwood for hardwood and softwood. The modelling procedures of each scenario was obtained by changing the wood species and the geographical representativeness of the study (for example, by using the Swedish electricity consumption mix instead of the global one). The system boundaries of these processes covered: sorting of logs, sawing of wood, drying and planing.

The GL_EU, LVL_EU, OSB_ EU and IJ_EU scenarios were modelled through the production processes available on the Ecoinvent database. The production process of GLT available in the Ecoinvent database (Wernet *et al.*, 2016) covers: the reception of rough wood and adhesives at the factory gate, the drying of rough wood, planing of lamellas, finger-joining of lamellas, gluing of lamellas with PVAc adhesive (UF), sawing of beams to boards, and planing of glulam.

The system boundary for the production of LVL begins with the reception of roundwood and adhesive (UF) at the factory gate, followed by the peeling of roundwood, stacking and cold pressing of veneers, hot pressing of veneers (between 80 ºC and 140 ºC), sanding, cutting to standard or ordered measurements, and grading according to quality requirements. The system boundary of the OSB production covers: the reception of logs at the factory gate, debarking of logs, slicing of logs into thin strands, drying of strands, mixing of strands with resin and a small quantity of wax, pressing or mixing at high pressure and high temperature, cutting of panels and packaging.

I-Joists are small beams composed of an upper and a lower flange (that can be made out of SW or LVL) glued perpendicularly to a central web of OSB. This study analysed the production of both types of I-joists – with LVL or SW flange materials. The system boundaries of both IJ products were similar, differing only in the type of flange product. The production of I-Joist beams began with the reception of web and flange materials at the factory gate, followed by the sizing of materials, assembling (using a phenolic adhesive), drying of the product and preparing products for delivery.

The inputs and outputs of the processes were those given by the Ecoinvent processes. In this study, the global representativeness of the Ecoinvent database processes representativeness was changed to correspond to the European representativity.

5.3.1.2 **Preservative treatments (Stage A1-A3)**

The preservative treatments production was modelled based on the Ecoinvent database processes and on the technical files of treatment products. The pressurised and surface treatment products' manufacturing was modelled based on the Ecoinvent database processes for these types of treatments. The production processes were adapted to correspond to a European representativity. In addition, the European preservative products application processes were adapted to have a Portuguese representativity.

Preservative products were applied in various wood species from different origins. The wood species and origins modelled were those referred in Section 5.3.1.1. As Spruce and Scots pine had two origins of products, the scenario modelled was the one closer to the deck construction place, which was Germany.

5.3.2 Construction stage (Stage A4-A5)

The construction stage comprised both the transportation from factory to the building site (Lisbon) (Stage A4) and the construction stage (Stage A5). As the production of structural products had different locations in Europe, the transportation to the construction place depended on the type of product. The production countries of construction products assumed in this study were those specified by an importing Portuguese company. Thus, France, Czech Republic, Germany and the United Kingdom were assumed as the origin countries of GLT, LVL, OSB, and I-Joist, respectively. The origin of products produced in Portugal was in Sertã, in the Centre region of Portugal, since it is the location of the company inventoried in Stage A3. The origin of other products (such as treatment products) was assumed to be in Lisbon.

In the Portuguese scenario, the construction of wood floors consists in the manual application of beams, or when possible, by a crane. The construction operations were excluded from the system boundaries because they are similar for all structural products under study and, as stated in the literature review, their influence on the life cycle impacts of wood products is small when compared with the whole life cycle impacts.

5.3.3 Use stage (Stages B1-B7)

The use stage covered the operations from the end of the construction stage until the deconstruction of the building. The literature review refers that structural timber does not need maintenance, repair, replacements, changes during refurbishment, or any operational energy or water consumption when applied in a controlled environment (for example, inside a construction, not exposed to the weather and wetting). When timber is applied outside, the corresponding operations of degradation of wood’s durability must be considered.

The operations modelled during the use of deck elements were the leaching of treatment products and the maintenance/reapplication of preservative treatments. For deck products treated with penetrating treatments, there are various types of maintenance: retreatment of treated products, replacement of treated products, and application of surface treatments. This study assumed the retreatment of wooden products in both case studies (PT and ST). Chapter 8 compared those scenarios with alternative scenarios for maintenance of wooden products.

5.3.4 End-of-life (Stages C1-C4)

The end-of-life stage covered the operations from the beginning of dismantling and/or deconstruction of construction elements until the disposal of wastes and/or reuse of materials. This study modelled and compared various scenarios for the end-of-life of wooden products, namely landfill and incineration. Those stages were modelled for wood products used in residential floors and exterior decks. Due to the chemical components embedded in treated wood products used in the exterior deck, only the incineration without energy recovery scenario (legal end-of-life scenario for treated wood in the European context) was considered. The dismantling operations of wooden floors' products are performed manually or with a crane. For all the scenarios studied, the dismantling operations are similar. For this reason, the operations of deconstruction were not considered.

The system boundaries of the end-of-life stage of landfill scenarios cover operations of transportation of materials to the landfill place, and landfilling operations. Those of the end-of-life stage of incineration scenarios cover operations of transportation of materials to the incineration plant and incineration operations. The system boundaries of the end-of-life stage of incineration with energy recovery cover the same operations as incineration scenarios but consider the energy produced as output. This output is taken into account in Module D.

5.3.5 Benefits and loads beyond the product system boundary (Module D)

This stage intends to model the benefits and loads resulting from the reuse, recycling and energy carriers leaving the product system. Due to its energetic properties, wood products and/or wood waste can be used as a source of energy at their end-of-life. This stage considers therefore the incineration with energy recovery of wood waste generated during the end-of-life of structures (wood dismantled at the end-of-life). Those results are shown in Section 8.

Those operations were considered by modelling the transportation of wood products to the incineration plant, the incineration, and the output of energy to the Portuguese energy grid.

5.4 **Conclusions**

This chapter describes the goal and scope of this study (i.e., case studies, data collection methodologies, cut-off criteria, allocation procedures and data quality requirements; and functional units and system boundaries). Firstly, the case studies assessed in this study were defined. The case studies include roundwood production, structural products production, and structural and durability solutions. For roundwood, the various case studies modelled vary in terms of forest management scenarios considered (operations performed during the forest management, wood species and country of origin). For structural products and solutions, the various case studies differ in terms of wood species, country of origin (for SW) and type of products. For durability solutions, the case studies vary in terms of wood species, preservative treatment application methodology, and preservative treatment product. Moreover, the data collection methodologies, cut-off criteria, allocation procedures and data quality requirements followed in this study were presented for each case study.

The functional units and system boundaries were describer for three different levels of assessment: forest management, production of construction products, and building solutions. At the forest management level, the functional unit was one cubic meter of roundwood at the forest road and the system boundary covers operations of site preparation, stand establishment and tending, and logging operations. At the production of construction products level, the functional unit was one cubic meter of construction product, and the system boundary covers the production phases (stages A1-A3, i.e., operations of raw materials extraction, transportation of raw materials to the factory gate and production of construction products).

At the building solutions level, the functional unit of structural solutions was the minimum volume of wood and/or wood-based structural product that complies with the structural requirements given by European standards for the design of an interior floor (4x4 m^2), for 50 years. The functional unit of the durability solution was the minimum amount of wood and preservative product necessary to maintain the durability of wood elements under a Use Class 3.1 exposure for 30 years. The system boundary of both scenarios covers the entire life cycle of wood-based and of preservative products (production (stage A1-A3), construction (stage A4-A5), use (B1-B7), and end-of-life (C1-C4)).

6 LIFE CYCLE INVENTORY (LCI)

6.1 LCI methodology

The LCI of this study followed the procedures described in Section 2.2.2. The data was collected from two different sources: generic and site-specific data. Generic data sources were LCA databases (e.g., Ecoinvent (Wernet *et al.*, 2016)). Site-specific data were calculated from companies' inquiries and, whenever necessary, using LCA databases as background data.

The data inventoried was geographically, and technologically limited to the European region and its industrial technology. The time related coverage of the LCI varied with the collection methodology. For data collected in LCA databases, processes of the last decade were chosen. For data collected in companies' inquiries, data representative of one year of the last decade was collected (2010-2020).

6.2 Life Cycle Stages

6.2.1 Roundwood production (A1)

As described in Section 5.3, the inventory of Portuguese processes was performed through companies' inquiries. The inventory of Swedish and Germany's processes was achieved through the data available in the Ecoinvent 3.6 database (Wernet *et al.*, 2016). Data was collected for the management operations of a hectare of forest land. In order to obtain the results per cubic meter of roundwood under bark, the inputs and outputs were divided by the total volume of roundwood produced. The total volume of roundwood produced per hectare of land, the volume of co-products produced per hectare of land, stands' productivity, dry wood density and the rotation period of each scenario are shown in Table 44.

The inputs and outputs of operations performed during the forest growth of Maritime pine, Cryptomeria and Eucalyptus (described in Section 5.3.1.1) were modelled using data provided by Portuguese governmental offices and associations reports, and the Ecoinvent database (Wernet *et al.*, 2016) processes. The modelling procedures based on the Ecoinvent was performed through agricultural and forest processes available in this database. The processes used to model the operations within the system boundaries are shown in Table 45.

Table 44 - Total volume of roundwood produced per hectare of land, volume of co-products produced per hectare of land, stands' productivity, dry wood density and rotation period of various scenarios

	Total	**Round-wood**	**Biomass**	**Productivity**	**Dry wood density**	**Rotation period**
	m^3	m^3	m^3	m^3/ha/year	kg/m^3	Year
MP_Seed_PT	504.8	412.8	92.0	8.0	561.8	45.0
MP_Plant_PT	499.2	412.8	86.4	8.0	561.8	45.0
MP_NR_PT	499.2	412.8	86.4	8.0	561.8	45.0
Euc_Plant_PT	744.0	697.5	46.5	15.5	852.0	45.0
Crypt_Plant_Pt	557.7	429.0	128.7	14.3	290.8	30.0
SPrc_Plant_DE	977.0	860.0	117.0	9.8	430.0	100.0
Spine_Plant_DE	768.0	660.0	108.0	6.4	490.0	120.0
SPrc_Plant_SE	542.0	503.0	39.0	9.0	430.0	80.0
Spine_Plant_SE	426.0	395.3	30.7	6.5	490.0	80.0

Table 45 – Ecoinvent process used to model operations of various forest management scenarios within the system boundary

Forest operations		**Database operations**
Site preparation	Harrowing with disk harrow	Tillage, harrowing, by offset disk harrow {row}| tillage, harrowing, by offset disk harrow | Cut-off, U
	Ploughing	Tillage, ploughing {row}| processing | Cut-off, U
	Subsoiling with subsoiler plow	Tillage, subsoiling, by subsoiler plow {row}| tillage, subsoiling, by subsoiler plow | Cut-off, U
	Road construction	Diesel, burned in building machine {GLO}| processing | Cut-off, U
	Road maintenance	Diesel, burned in building machine {GLO}| processing | Cut-off, U
Stand establishment and tending	Seedling	Tree seedling, for planting {RER}| tree seedling production, in unheated greenhouse | Cut-off, U
	P fertilising	Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, U
	N fertilising	Nitrogen fertiliser, as N {GLO}| market for | Cut-off, U
	Mechanical weed control with forwarder	Tillage, harrowing, by offset disk harrow {row}| tillage, harrowing, by offset disk harrow | Cut-off, U
	Thinning and pruning with power saw	Power sawing, without catalytic converter {RER}| processing | Cut-off, U
	Forwarding of thinned logs with forwarder	Forwarding, forwarder {RER}| forwarding, forwarder | Cut-off, U
Logging operations	Final harvesting with harvester	Harvesting, forestry harvester {RER}| harvesting, forestry harvester | Cut-off, U
	Extraction with tractor	Delimbing/sorting, excavator-based processor {RER}| delimbing, with excavator-based processor | Cut-off, U
	Forwarding with forwarder	Forwarding, forwarder {RER}| forwarding, forwarder | Cut-off, U

The processes for construction and maintenance of roads were not found in the database. The modelling procedures of those processes was made based on the LCI performed by Dias *et al.* (2007), which found that the consumption of diesel for those operations is 8.27 MJ and 7.72 MJ, respectively, for each operation of a forest road area of 249.55 m^2/ha as given by Ferreira *et al.* (2021). The diesel consumption was modelled by "Diesel, burned in building machine {GLO}| processing | Cut-off, U" process.

In addition to the processes identified in Table 45, this study also considers inputs from environment, such as: "Carbon dioxide, in air", "Solar energy" (equal to the gross calorific value of wood species), "Wood, soft, standing", "Transformation, from forest, extensive", "Transformation, from forest, intensive", "Transformation, from traffic area, rail/road embankment", "Transformation, to traffic area, rail/road embankment" and "Land occupation forest". These inputs were quantified according to the information given by Ferreira *et al.* (2021) and the quantities modelled are shown in Table 46 and Table 47. These inputs are grouped in "Land occupation" and "Biomass related inputs". The carbon content of each Portuguese product was calculated according to Equation 1, given by the EN 16449 (CEN, 2014a), and is shown in Table 48.

Table 46 – Biomass related inputs of various forest management scenarios

Forest scenario	**Rotation period**	**Total volume per ha**	**Biomass related inputs**		
			Wood	Energy	Carbon
Units	years	m^3	m^3	MJ	kg
MP_Seed_PT	45	504.8	1.00	10994.8	1030.9
MP_Plant_PT	45	499.2	1.00	10994.8	1030.9
MP_NR_PT	45	499.2	1.00	10994.8	1030.9
Euc_Plant_PT	45	744.0	1.00	15744.1	1563.3
Crypt_Plant_Pt	30	557.7	1.00	6446.8	533.6
SPrc_Plant_DE	100	977.0	1.00	8772.0	778.9
Spine_Plant_DE	120	768.0	1.00	9996.0	887.5
SPrc_Plant_SE	80	542.0	1.00	8772.0	778.9
Spine_Plant_SE	80	426.0	1.00	9996.0	887.5

The inputs and outputs of Portuguese scenarios, and the quantity considered for each scenario per cubic meter of wood, are shown in Table 49. The yield of logging operations (hours of work per cubic meter of wood) was determined based on data given by Dias *et al.* (2007). The yield of the other operations was given by the Ecoinvent database per each hectare of land.

This study also considers data calculated by national offices (ICNF, DGRF, DNGF) and industry associations' (AIFF) reports, which provide representative values for Portuguese scenarios. These reports quantified the inputs and outputs of diesel, petrol and lubricants combustion, and use in machinery, per hour of work (litters per hour), and the yield of machinery (hour per ha). The data from these reports was summarised by Dias & Arroja (2012). The background data of these processes were obtained from the Ecoivent database. The results of this modelling procedures were compared in Chapter 8 with the ones from previous studies.

The inputs and outputs of the production of Spruce and Pinus Sylvestris roundwood were those given by the Ecoinvent database. These flows are shown in Table 50.

Table 47 – Land use inputs of various forest management scenarios

	Transformation, from and to forest	**Transformation, from and to traffic area**	**Land occupation**	**Traffic road occupation**
	m^2/m^3	m^2/m^3	$m^2.year/m^3$	$m^2.year/m^3$
MP_Seed_PT	19.3	0.49	869.2	22.2
MP_Plant_PT	19.5	0.50	878.9	22.5
MP_NR_PT	19.5	0.50	878.9	22.5
Euc_Plant_PT	13.1	0.34	589.7	15.1
Crypt_Plant_Pt	17.5	0.45	524.5	13.4
SPrc_Plant_DE	10.0	0.22	1001.4	22.1
Spine_Plant_DE	12.7	0.28	1528.8	33.8
SPrc_Plant_SE	18.4	0.07	1470.4	5.59
Spine_Plant_SE	23.4	0.09	1870.8	7.12

Table 48 – Calculation of carbon content of each Portuguese product

Wood species	**Density**	**Density at 0% of Moisture Content (MC)**	**Amount of carbon dioxide**
	kg/m^3	kg/m^3	kg/m^3
Maritime pine	597	561.8	1030.9
Eucalyptus	905.3	852.0	1563.3
Cryptomeria	309	290.8	533.6

6.2.2 Transport to the sawmill (A2)

The data for modelling procedures the processes of transport of Portuguese wood species from the forest to the sawmill was calculated through inquiries to the sawmill inventoried in stage A3. The mean distances from forests (in Centro region) to the sawmill (Sertã) were considered. The mean distance from Maritime pine forests to the sawmill was 210 km. As the national distribution of Eucalyptus and Maritime pine forests is similar, the same distance for Eucalyptus and Maritime pine scenarios was considered. As the distribution of Cryptomeria in Portugal is limited to the Azores islands, this study assumed that the transportation of Cryptomeria from the Azores (São Miguel Island) to the port of Lisbon was performed through a cargo ship, and that the transportation from the port of

Lisbon to Sertã was performed by a lorry. The distances considered were 1613 km and 196 km, respectively. The inventory data used to model the transportation is shown in Table 51. The processes used to model the transportation by truck and ship were, respectively: “Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U” and “Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, U”, respectively.

Table 49 – LCI of Portuguese forest management scenarios per cubic meter of roundwood

Forest management operations	**Unit**	**MP_Seed_PT**	**MP_Plant_PT**	**MP_NR_PT**	**Euc_Plant_PT**	**Crypt_Plant_Pt**
Tillage, harrowing, by offset disk harrow {RoW}| tillage, harrowing, by offset disk harrow | Cut-off, U	ha	0.0079	0.010	0.0060	0.0013	0.0090
Tillage, ploughing {RoW}| processing | Cut-off, U	ha	0.0020	0.0020	0.0020	0.0134	0.0018
Tillage, subsoiling, by subsoiler plow {RoW}| tillage, subsoiling, by subsoiler plow | Cut-off, U	ha	0.0020	0.0020	-	0.0013	0.0018
Tree seedling, for planting {RER}| tree seedling production, in unheated greenhouse | Cut-off, U	p	-	2.8045	-	1.6801	-
Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, U	kg	0.3566	0.3606	-	0.5645	-
Nitrogen fertiliser, as N {GLO}| market for | Cut-off, U	kg	0.2773	0.2804	0.2804	0.2419	-
Power sawing, without catalytic converter {RER}| processing | Cut-off, U	hr	0.0713	0.0721	0.0721	0.0242	0.0484
Harvesting, forestry harvester {RER}| harvesting, forestry harvester | Cut-off, U	hr	0.0499	0.0505	0.0505	0.0938	0.0538
Delimbing/sorting, excavator-based processor {RER}| delimbing, with excavator-based processor | Cut-off, U	hr	0.0571	0.0577	0.0577	0.0750	0.0615
Forwarding, forwarder {RER}| forwarding, forwarder | Cut-off, U	hr	0.0200	0.0200	0.0200	0.0200	0.0200
Road construction	ha	0.0020	0.0020	0.0020	0.0013	0.0018
Road maintenance (45 years)	ha	0.0178	0.0160	0.0160	0.0108	0.0179
Excavation, hydarulic digger {RER} | processing | Cut-off, U		-	-	-	0.4200	-

The transport of roundwood from Pinus Sylvestris and Spruce forests to the sawmills was determined based on the mean distances given by the Ecoinvent database reports. According to the Ecoinvent database, the mean distance representative of the European scenario is 75 km. The process used to model this transportation was “Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Cut-off, U”.

Table 50 - LCI of Spruce and Scots pine forest management scenarios per cubic meter of roundwood

Forest management operations	**Unit**	**Spine_Plant_DE**	**SPrc_Plant_DE**	**SPrc_Plant_SE**	**Spine_Plant_SE**
Forwarding, forwarder {RER}| forwarding, forwarder | Cut-off, U	hr	0.0260	0.0220	0.0478	0.0487
Gravel, crushed {RoW}| market for gravel, crushed | Cut-off, U	kg	108.0	70.74	7.340	9.3403
Harvesting, forestry harvester {RER}| harvesting, forestry harvester | Cut-off, U	hr	0.0195	0.0166	0.0979	0.0979
Power sawing, without catalytic converter {RER}| processing | Cut-off, U	hr	0.4632	0.4746	0.0562	0.1060
Skidding, skidder {RER}| skidding, skidder | Cut-off, U	hr	0.0677	0.0741	0.0013	0.0013
Tree seedling, for planting {RER}| tree seedling production, in unheated greenhouse | Cut-off, U	p	10.416	3.070	5.534	3.335
Diesel, burned in building machine {GLO} | market for | Cut-off, U	MJ	14.055	8.783	10.72	7.932

The modelling procedures considered that the trucks return empty to the forest and for that reason, the kilometres were multiplied by 2. The transport by sea considered that the container ships return loaded, and, for that reason, the distance assumed was the distance between the forest and the sawmill.

Table 51 – Distances used for modelling procedures the transportation processes of roundwood from forest to the sawmill gate

SW scenarios	**Distance**			**Distance per cubic meter**		
	Density	Road	Sea	By road	By road (with return)	By sea
Units	kg/m^3	km	km	ton.km	ton.km	ton.km
SW_MP_PT	597.0	210.0		125.4	250.7	
SW_Euc_PT	905.3	210.0		190.1	380.2	
SW_Cryp_PT	309.0	196.0	1613.0	60.6	121.1	498.4
SW_SPrc_SE	430.0	75.0		32.3	64.5	
SW_SPrc_DE	430.0	75.0		32.3	64.5	
SW_SPine_SE	490.0	75.0		36.8	73.5	
SW_SPine_DE	490	75		36,8	73,5	

6.2.3 Structural wooden products production (A3)

6.2.3.1 Sawnwood

The inventory of Maritime pine sawnwood production processes was performed through inquiries to a sawmill company located in Sertã, Portugal. This company consumed 358 451 cubic meters of roundwood under bark during 2016, which represents approximately 20% of the wood that was consumed by Portuguese sawmills (Pinus, 2017). The inputs and outputs were quantified by data collection sheets developed based on Annex A of EN 14044 (ISO, 2006c). The inventoried company stated that the main origin of the roundwood consumed was from naturally regenerated forests. The background processes (such as water production, energy production, etc.) were modelled using the Ecoinvent database processes. The modelling procedures of sawmilling of Maritime pine is shown in Table 52. The data directly collected from the company was not reported in this study due to confidentiality issues.

Table 52 – LCI of Maritime pine sawnwood production

Outputs		
Sawnwood	1.00	m^3
Inputs	Amount	Unit
MP_NR_PT	4.51	m^3
Electricity, low voltage {PT}| market for | Cut-off, U	40.37	kwh
Tap water {RER}| market group for | Cut-off, U	38.87	kg
Diesel, burned in building machine {GLO}| processing | Cut-off, U	79.96	MJ
Packaging film, low density polyethylene {GLO}| market for | Cut-off, U	0.42	kg
Lubricating oil {RER}| market for lubricating oil | Cut-off, U	0.10	kg
Emissions		
Particulates, unspecified	1.51	g
Carbon monoxide	21.30	g
Nitrogen oxides	8.28	g
Organic substances, unspecified	5.68	g
Waste generated		
Waste mineral oil {Europe without Switzerland}| treatment of waste mineral oil, hazardous waste incineration | Cut-off, U	5.03	g
Hazardous waste, for incineration {GLO}| market for | Cut-off, U	4.50	g

The inventory of Cryptomeria, Scots pine and Spruce sawnwood production was performed through the processes available on the Ecoinvent database for sawnwood production. The Ecoinvent processes used to model these ones are representative of the global production of sawnwood. These processes were: “Sawnwood, softwood, raw {RoW}| sawing, softwood | Cut-off, U”, “Sawnwood, beam, softwood, raw, dried (u=10%) {RoW}| beam, softwood, raw, kiln drying to u=10% | Cut-off, U” and “Sawnwood, beam, softwood, dried (u=10%), planed {RoW}| planing, beam, softwood, u=10% | Cut-off, U”, respectively. The inputs and outputs of these processes are shown in Tables C-1, C-2, and C-3 of Annex C, respectively.

The inventory process of Eucalyptus was similar to the procedure followed for modelling procedures of Cryptomeria, Scots pine and Spruce. The processes used for modelling procedures were: “Sawnwood, hardwood, raw {RoW}| sawing, hardwood | Cut-off, U”, “Sawnwood, beam, hardwood, raw, dried (u=10%) {RoW}| beam, hardwood, raw, kiln drying to u=10% | Cut-off, U” and “Sawnwood, beam, hardwood, dried (u=10%), planed {RoW}| planing, beam, hardwood, u=10% | Cut-off, U”. The inputs and outputs of these processes are shown in Table D-1, D-2, and D-3 of Annex D, respectively.

The inputs and outputs of these processes were adapted to be representative of the wood species and the production country (Germany, Sweden and Portugal). The energy mixes of Sweden, Germany and Portugal were changed to the country specific energy consumption scenario, i.e., “Electricity, medium voltage {SE}| market for | Cut-off, U”, “Electricity, medium voltage {DE}| market for | Cut-off, U”, and “Electricity, medium voltage {PT}| market for | Cut-off, U”, respectively. Inputs and outputs of wood processes were adapted to the Spruce and Scots pine operations modelled in stage A1.

6.2.3.2 **Glulam, LVL, I-Joist and OSB**

Glulam, LVL and I-Joist production processes were inventoried using the processes available in the Ecoinvent database. The production stage of GLT was modelled using “Glued laminated timber, for indoor use {RER}| production | Cut-off, U” process. LVL and OSB productions were modelled using “Plywood, for indoor use {RER}| production | Cut-off, U” and “Oriented strand board {RER}| production | Cut-off, U”, respectively. The IJ production process was modelled based on “Joist, engineered wood {RoW}| engineered wood joist production | Cut-off, U” process. The volumes of SW, LVL and OSB used in the IJ production process were adjusted to the C24, LVL and OSB volumes calculated for each scenario. The representativeness of inputs and outputs processes of I-Joists was changed to Europe.

6.2.4 Preservative treatments (A1-A3)

The LCI of stages A1-A3 of preservative treatments covered the: preservatives production, their transportation to the treatment place and preservative treatment application. The inventory of preservatives production was modelled based on the chemical compositions given by the ECHA reports and technical sheets. The compounds’ production processes were obtained from the Ecoinvent 3.6 database (Wernet *et al.*, 2016). The consumption of water and electricity, and the generation of waste, during the PT and ST preservative's production stage were modelled using the "Wood preservative, inorganic salt, containing Cr {GLO}" and "Wood preservative, organic, outdoor use, no ground contact {GLO}" Ecoinvent processes, respectively. The inventories of PT and ST are shown in Table 53 and Table 54, respectively.

Table 53 – LCI of PT production process

Process	Amount	Unit
Preservative PT (production)	1	kg
Inputs		
Chemical factory, organics {GLO}| market for | Cut-off, U	4.00E-10	p
Cyclic N-compound {GLO}| market for | Cut-off, U	1.6	g
Copper oxide {GLO}| market for | Cut-off, U	145.7	g
Triazine-compound, unspecified {GLO}| market for | Cut-off, U	1.6	g
Ammonium chloride {GLO}| market for | Cut-off, U	0.5	g
Ammonium carbonate {GLO}| market for | Cut-off, U	0.5	g
Diethanolamine {GLO}| market for | Cut-off, U	269.1	g
Water, deionised {RoW}| market for water, deionised | Cut-off, U	572	g
Electricity, medium voltage {GLO}| market group for | Cut-off, U	36.1	Wh
Outputs		
Hazardous waste, for incineration {RoW}| market for hazardous waste, for incineration | Cut-off, U	64	g

Table 54 - LCI of ST production process

Process	Amount	Unit
Preservative ST (production)	1	kg
Inputs		
Chemical factory, organics {GLO}| market for | Cut-off, U	4.00E-10	p
Cyclic N-compound {GLO}| market for | Cut-off, U	0.5	g
[thio]carbamate-compound {GLO}| market for | Cut-off, U	0.5	g
Triazine-compound, unspecified {GLO}| market for | Cut-off, U	1.6	g
Chemical, organic {GLO}| market for | Cut-off, U	25.1	g
Pyrethroid-compound {RoW}| production | Cut-off, U	0.8	g
Naphtha {RoW}| market for | Cut-off, U	971.5	g
Electricity, medium voltage {GLO}| market group for | Cut-off, U	42.8	Wh
Outputs		
Hazardous waste, for incineration {RoW}| market for hazardous waste, for incineration | Cut-off, U	2.24	kg

The application of PT in wood elements was modelled considering the "Wood preservation, vacuum pressure method, inorganic salt, containing Cr, outdoor use, ground contact {RoW}" Ecoinvent process. The values used to model the inputs of tap water, chemical products to treat the wastewater, electricity production and emissions to water and to the air are given by the referred process. Emissions to the water resulting from the application of PT treatments were calculated according to the OECD report (OECD, 2013). As an example, the calculation of tebuconazole emissions is shown below. The inputs and outputs for this process are presented in Table 55.

Table 55 – LCI of the application of 1 kg of preservative PT

Process	**Amount**	**Unit**
Application of 1 kg of preservative PT	1	kg
Inputs		
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	10.6	g
Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, U	25	g
Tap water {RoW}| market for | Cut-off, U	25	kg
Wood preservation facility, vacuum pressure method {GLO}| market for | Cut-off, U	2.22	p
Electricity, medium voltage {GLO}| market group for | Cut-off, U	416	Wh
Preservative PT (production)	1	kg
Emissions to air		
Water/m^3	0.025	m^3
Emissions to water		
Copper	1.457	mg
Tebuconazole	0.48	mg
DDAC	30	mg
Propiconazole	2.4	mg

The emissions to the water resulting from the vacuum pressure treatment process are given by equation (4.27) of the OECD report (OECD, 2013), which is shown in Equation (21).

$$E_{water}[kg] = Q_{sa}\ [kg/m^3] \times Vol_{wood}[m^3] \times F_{solub} \qquad (21)$$

Where, E_{water} is the amount of substance released to the water, Q_{ai} is the quantity of substance applied per m³ of wood, Vol_{wood} is the volume of wood to be treated and F_{solub} is the solubility factor that takes into account the solubility of the substance in water (given by Table 4.8 of the OECD report (OECD, 2013)).

The quantity of tebuconazole per m^3 of wood (E_{water}) is given by Table 35 [0.0016 kg/m^3]. As Equation 21 intends to calculate the amount of tebuconazole released per cubic meter of wood, then Vol_{wood} is equal to 1 [m^3]. According to the ECHA report for tebuconazole (ECHA, 2020), the solubility of tebuconazole is 29 mg/l, which corresponds to a solubility factor of 0.003, according to the OECD report (OECD, 2013). Therefore, the amount of tebuconazole released to the water is 0.480 mg per kilogram of preservative product applied.

The application of preservative ST in wood is made manually with a painting brush. The emissions to the soil arising from this process were modelled assuming a loss factor of 3% of active substances. The inputs and outputs of the PT application process are shown in Table 56.

Table 56 - LCI of the application of 1 kg of preservative ST

Process	**Amount**	**Unit**
Application of 1 kg of preservative ST	1	kg
Inputs		
Preservative ST (production)	1	kg
Emissions to water		
Cypermethrin	24	mg
Tebuconazole	15	mg
Carbamic acid, butyl-, 3-iodo-2-propynyl ester	15	mg
Propiconazole	48	mg

6.2.5 Transport (A4)

The transportation to the construction site depends on the location of the production factories. The construction site was considered to be in Lisbon (Portugal). Due to the availability of Maritime pine, Eucalyptus and Cryptomeria in the national market, a distance of 210 km was considered for Portuguese products (from Sertã to Lisbon). Germany and Sweden’s products are transported from origin countries to Lisbon, which represents a distance of 2,443 km and 3,608 km, respectively. GLT, LVL, OSB and IJ products used in Portuguese construction are imported. The import market of a Portuguese company was considered. Thus, France, Czech Republic, Germany, and the United Kingdom were assumed as origin countries of GLT, LVL, OSB and I-Joist, respectively. The distances from these countries to Lisbon are 1,318 km, 2,629 km, 2,443 km and 2,030 km, respectively. The modelling procedures assumed that the return of the truck to the place of origin is made with the truck fully loaded.

The transportation of Portuguese products was modelled using the “Transport, freight, lorry 7.5-16 metric ton, EURO3 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO3 | Cut-off, U” process, and the transportation of imported sawnwood, GLT, LVL, OSB and IJ was modelled using the “Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, U” process. The densities considered in the modelling procedures of the transportation of products and the tonne-kilometres are shown in Table 57.

Table 57 – Distances of structural products from factory gate to the construction places

Structural products	Country of origin	Distance	Density	Transportation process per m^3
		km	km/m^3	ton.km
SW_MP_PT	Portugal	210	597	125.37
SW_Euc_PT	Portugal	210	905.3	190.113
SW_Cryp_PT	Portugal	210	309	64.89
SW_SPine_SE	Sweden	3608	490	1767.92
SW_ SPrc _SE	Sweden	3608	430	1551.44
SW_SPine_DE	Germany	2443	490	1197.07
SW_ SPrc _DE	Germany	2443	430	1050.49
GLT	France	1318	420	553.56
LVL	Check Republic	2629	510	1340.79
OSB	Germany	2443	550	1343.65
IJ_C24 and IJ_LVL	United Kingdom	2030	3.29	6.6787

6.2.6 Use (B1-B7)

The inputs and outputs of the use phase of wood structures are related to the exterior deck case study. During the use of treated wooden decks, the OECD report (OECD, 2013) refers that the soil receives the majority of products leached. The emissions to the soil were calculated according to the equation (4.44) and table 4.15 of the OECD report (OECD, 2013). The calculation of PT and ST products leaching is similar and it is explained below, for tebuconazole leached from ST products.

According to the OECD report (OECD, 2013), the amount of product leached to the soil can be given by:

$$Q_{soil}[kg] = Area_{wood}\ [m^2] \times Q^*{}_{soil}\ \left[\frac{kg}{m^2}\right] \tag{22}$$

Where Q_{soil} is the amount of substance leached to the soil, $Area_{wood}$ is the leachable wood area, and $Q^*{}_{soil}\ \left[\frac{kg}{m^2}\right]$ is the quantity of product leached per square meter of wood over a certain period. The latter can be found on the ECHA reports of preservative treatments.

The reference flow of the process used is 1 kg of preservative treatment applied, which means that the amount of substance leached is given in terms of kg of applied product. Then, instead of being multiplied by the leachable wood area, the quantity of product leached per square meter of wood over a given period is divided by the application rate - 200 g/m^2.

According to the ECHA report for ST (PPG AC - France SA, 2019), the rate of tebuconazole leached per square meter of wood is 0.0125 mg per m^2 of wood elements per day, which represents a total of 0.0624 mg/kg of preservative applied leached per day. As the maintenance operation is made every two years, and in order to be related to the reference flow, the referred rate shall be multiplied by 730 days (2 years). Therefore, the amount of substance leached to the soil is 45.53 mg per kg of preservative product applied. The use stages of PT and ST products per maintenance operation are shown in Table 58 and in Table 59, respectively.

Table 58 – LCI of leaching of PT active substances during 15 years of use per kg of treatment applied

Process	**Amount**	**Unit**
Leaching of PT active substances during 15 years of use per kg of treatment applied	**1**	**kg**
Emissions to soil		
Copper	4.71	g
Tebuconazole	3.14	mg
DDAC	2.98	mg
Propiconazole	6.56	mg

Table 59 - – LCI of leaching of ST active substances during 2 years of use per kg of treatment applied

Process	Amount	Unit
Leaching of ST active substances during 2 years of use per kg of treatment applied	1	kg
Emissions to soil		
Cypermethrin	3.89	mg
Tebuconazole	45.5	mg
Carbamic acid, butyl-, 3-iodo-2-propynyl ester	22	mg
Propiconazole	122.2	mg

6.2.7 End-of-life (C1-C4)

The end-of-life phase of wooden structures differs for both case studies. The scenarios of deck elements consider that, at the end of life, the products are incinerated. The end-of-life scenarios for the residential case study considers incineration (with and without energy recovery) and landfill.

For each scenario, it was assumed for stage C2 that the building is 100 km away from the waste processing factory. The transportation of all the products was modelled with the "Transport, freight, lorry 7.5-16 metric ton, EURO3 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO3 | Cut-off, U" process. The tonne-kilometres considered for each scenario are shown in Table 60.

Table 60 – Distances and data used to model the transportation process from the construction place to the end-of-life manufacturing factory

Structural product	**Density**	**Distance**	**Transportation process per m^3**
Unit	kg/m^3	km	ton.km
SW_MP_PT	597	100	59.7
SW_Euc_PT	905.3	100	90.5
SW_Cryp_PT	309	100	30.9
SW_SPine_SE	490	100	49.0
SW_ SPrc _SE	430	100	43.0
SW_SPine_DE	490	100	49.0
SW_ SPrc _DE	430	100	43.0
GLT	420	100	42.0
LVL	510	100	51.0
OSB_	550	100	55.0
IJ_C24 and IJ_LVL	3.29	100	0.33

6.2.7.1 **Incineration of deck products**

Doka (2003) refers that the emissions resulting from the combustion of organic treatments (such as ST) have small effects on the environment. However, the combustion of inorganic preservatives (such as PT) can release significant levels of heavy metals and non-metals (Doka, 2003).Therefore, the incineration of PT products was modelled with "Waste building wood, chrome preserved {RoW}| treatment of, municipal incineration" process from the Ecoinvent database, and the incineration of ST products was modelled with "Waste wood, untreated {RoW}| treatment of waste wood, untreated, municipal incineration" generic process from the same database. The carbon emissions of those processes were changed to consider that the whole carbon dioxide sequestered during the trees' growth is released during the combustion of wood. The reference unit of this process was one kilogram of treated wood. As the wood species vary in density, an incineration scenario for each wood specie was modelled. For a total volume of 0.6 m^3 (volume of wood products), the wood mass of each scenario is shown in Table 61. As the products treated with PT are replaced once during the service life, the volume of treated wood burned doubles.

Table 61 – Mass of wooden products incinerated at the end-of-life (without energy recovery)

Products	**Type of treatment**	
	ST	Pt
Units	kg	kg
SW_MP_PT	358.2	716.4
SW_Euc_PT	543.2	-
SW_Cryp_PT	185.4	370.8
SW_SPine_DE	294.0	588.0
SW_ SPrc _DE	258.0	-

In sum, the LCI of durability scenarios proposed in Table 4 required the definition of eight scenarios: Maritime pine treated with PT (MP-PT); Cryptomeria treated with PT (CR-PT); Scots pine treated with PT (SPine-PT), Maritime pine treated with ST (MP-ST), Cryptomeria treated with ST (CR-ST), Scots pine treated with ST (Spine-ST), Spruce (Sprc-ST) treated with ST; and Eucalyptus treated with ST (Euc-ST).

6.2.7.2 **Incineration of residential floor products**

At the waste processing stage, it was assumed that the wood products are burned for energy recovery (stage C3) and that the energy produced goes back to the Portuguese electricity grid (module D). These operations were modelled by the following processes from the ELCD database (Cristina, 2016): “Waste incineration of untreated wood (10.7% water content), EU-27”, and “Waste incineration of wood products (OSB, particle board), EU-27”, for products that do not use adhesives and for products that use adhesives (GLT, LVL, and I-Joists), respectively.

The modelling procedures considers that the whole carbon dioxide retained in wood products is released to the atmosphere. The carbon content released into the atmosphere per cubic meter of structural products (and linear meter for I-Joists) is presented in Table 62.

6.2.7.3 **Landfill of residential floor products**

The disposal of wood products in landfills exposes wood to the natural degradation agents, which leads to the biodegradation of these products. Cellulose and hemicellulose contained in wood are biodegradable and quickly decompose to small components. The disposal of the products was modelled by the following processes from the ELCD database (Cristina, 2016): “Landfill of untreated wood EU-27”, and “Landfill of wood products (OSB, particle board) EU-27”, for products that do not use adhesives and for products that use adhesives (GLT, LVL, and I-Joists), respectively.

Table 62 – Carbon dioxide released to the atmosphere per each cubic meter of structural product

Structural product	**Carbon dioxide content**
	kg CO_2/m^3
SW_MP_PT	1030.9
SW_Euc_PT	1563.3
SW_Cryp_PT	533.6
SW_SPine_SE	846.2
SW_ SPrc _SE	742.6
SW_SPine_DE	846.2
SW_ SPrc _DE	742.6
GLT	725.3
LVL	880.7
IJ_C24	745.1
IJ_LVL	888.0
OSB	949.8

As in the assumptions made by Santos *et al.* (2021), this study assumed that 40% of the carbon contained in wood is released to the atmosphere as carbon dioxide (CO_2) and 60% is released as methane (CH_4). The emissions of carbon dioxide and methane were calculated and changed in the process corresponding to the emissions of each product assessed. According to EN 16449, for each 100 kg of wood, 50 kg is carbon, and, according to Ramage *et al.* (2017b), approximately 3% of this amount is emitted as carbon dioxide (40%) and methane (CH_4) (60%). The carbon dioxide and methane emissions estimated per cubic meter of product are shown in Table 63.

6.3 **Conclusions**

This Chapter described the LCI procedures used to model the life cycle operations and presents the inventory data collected. Two methodologies for collection of data were considered: collection of data through inquiries to companies, and use of data from the Ecoinvent database (Wernet *et al.*, 2016). The data for Maritime pine, Eucalyptus and Cryptomeria forest management scenarios, transportation of roundwood of these scenarios to the sawmill, and sawing of Maritime pine was collected through inquiries to companies. The modelling procedures of the other scenarios was performed using data from the Ecoinvent database (Wernet *et al.*, 2016) with the same representativeness of data collected through inquiries to companies. In conclusion, the inputs and outputs of each life cycle operation were calculated and presented in this chapter.

Table 63 – Carbon dioxide and methane emissions during the landfilling of structural products

Structural products	**Carbon sequestered**	**CO_2 released**	**CH4 released**
Units	kg	kg	kg
SW_MP_PT	298.5	3.582	5.373
SW_Euc_PT	452.7	5.432	8.148
SW_Cryp_PT	154.5	1.854	2.781
SW_SPine_SE	245.0	2.940	4.410
SW_ SPrc _SE	215.0	2.580	3.870
SW_SPine_DE	245.0	2.940	4.410
SW_ SPrc _DE	215.0	2.580	3.870
GL_EU	210.0	2.520	3.780
LVL_EU	255.0	3.060	4.590
IJ (C24)	215.8	2.589	3.884
IJ (LVL)	257.1	3.085	4.628
OSB_ EU	275.0	3.300	4.950

7 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

7.1 LCIA methodology

The LCIA methodology followed in this study was that proposed by EN 15804+A2 (CEN, 2019). This method is aligned with the requirements of the Environmental Footprint 3.0 (EF) methodology (Zampori & Pant, 2019), except for the biogenic carbon account. The EN 15804+A2 (CEN, 2019) method considers that the emission of biogenic carbon causes the same impact than fossil carbon on Climate change indicator, but this impact can be neutralised through the remotion of this carbon from atmosphere by photosynthesis processes. In contract EF 3.0 methodology does not include biogenic carbon uptake and release.

The environmental impacts were calculated with SimaPro 9.1 software (M. Goedkoop *et al.*, 2016). SimaPro assigned the LCI results to the selected impact categories (classification) and calculates the corresponding results based on characterization factors given by EN 15804+A2. The software has a database of the most common LCIA methods where the category indicators and characterization, normalization and weighting factors are given.

This study calculates therefore the environmental impact categories given by the EN 15084+A2 (CEN, 2019). This standard divides the environmental categories into core environmental impact indicators and additional environmental impact indicators. The indicators of each category and their units are described in Section 7.2. Hayward (2016) refers that the Water use, Ecotoxicity (freshwater), Human toxicity and Land use related impacts /soil quality indicators shall be assessed with care because of the uncertainties and the limited experience of the calculation methods.

7.2 Impact categories

7.2.1 Core environmental impact indicators

7.2.1.1 Climate change

Climate change indicator quantifies the Global Warming Potential (GWP-t), also known as “greenhouse effect”, by quantifying the radiative forcing (W/m^2) by following the pulse emission of a given greenhouse gas in the present-day atmosphere integrated over a time horizon, compared to that of carbon dioxide. In other words, GWP-t can be described as the quantification of the total contribution of a gas to global warming resulting from the emission of one unit of that gas in relation to the contribution caused by one unit of carbon dioxide for a given period. This study uses the GWP-t calculation model given by IPCC 2013 (IPCC, 2014) to quantify the pulse emissions for a period of 100 years. This indicator is the sum of three sub-indicators, which are: Global Warming Potential fossil fuels (GWP-f), Global Warming Potential biogenic (GWP-b), and Global Warming Potential land use and land use change (GWP-luluc).

GWP-f indicator is related to greenhouse gas emissions originated from the oxidation or reduction of fossil fuels through their degradation or transformation, for example through combustion. GWP-b is related: i) to the emissions of carbon (CO, CO_2, and CH_4) resulting from the oxidation and reduction of aboveground biomass through their degradation or transformation; and ii) to the uptake of carbon from atmosphere through photosynthesis during biomass growth. GWP-luluc is related to carbon uptakes and emissions caused by stocks changes, which can result from land use change and land use, for example through deforestation operations.

7.2.1.2 **Ozone depletion potential**

The depletion potential of the stratospheric ozone layer (ODP) indicator is defined as the ratio of the change in global ozone for a given mass emission of the substance to the change in global ozone for the same mass emission of Trichlorofluoromethane (CFC-11) (WMO, 2014). In other words, ODP can be defined as the relative strength of a product or a process to destroy the stratospheric ozone layer.

7.2.1.3 **Acidification potential**

The acidification potential (AP) indicator is quantified by the Accumulated Exceedance model given by Seppala *et al.* (2006) and Posch *et al.* (2008). The AP is quantified in terms of H^+ releases without addressing the destiny of chemicals in air and in soil - emissions and following depositions. Acidification occurs mainly due to the emissions of NH_3, NO_2, NO, SO_2 and SO_3.

7.2.1.4 **Eutrophication potential**

The eutrophication potential (EP) indicator is subdivided into: Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-f), Eutrophication potential, fraction of nutrients reaching marine end compartment (EP-m), and Eutrophication potential, Accumulated Exceedance (EP-t). EP-f and EP-m indicators assess the effects of eutrophication on maritime ecosystems and EP-t assess the effects of eutrophication on terrestrial ecosystems. EP-f and EP-m indicators are quantified through the EU-TREND model (M. J. Goedkoop *et al.*, 2013) and are quantified in relation to PO_4^{3-} and N effects, respectively. EP-t is quantified through the Accumulated Exceedance model in terms of N releases.

7.2.1.5 **Photochemical ozone creation potential**

The formation potential of tropospheric ozone (POCP) indicator addresses the impacts from ozone and other oxygen compounds formed by the oxidation of Volatile Organic Compounds (VOC), under the influence of sunlight. POCP impacts are calculated by the LOTOS-EUROS model (van Zelm *et al.*, 2008) for the reference effects of Non-Methane Volatile Organic Compounds (NMVOC).

7.2.1.6 **Potential of depletion of abiotic resources**

The abiotic depletion potential (ADP) indicator is subdivided into: abiotic depletion potential for non-fossil resources (minerals and metals) (ADP-m) and abiotic depletion potential for fossil resources (ADP-f). In the nomenclature of EN 15804 (CEN, 2013d), this indicator is represented by ADPE. These indicators are quantified by the CML 2002 model (Guinee, 2002), which refers to the amount of resources that is available on earth, estimated by multiplying the average concentration of resources in the crust of earth by the mass of the crust. The ADP-m indicator is related to the depletion of minerals and metals and is expressed in kg of antimony equivalent, which is the reference element adopted by the CML 2002 model. The ADP-f indicator quantifies the depletion of fossil fuels, such as oil, natural gas and coal, and is expressed in Megajoules (MJ).

7.2.1.7 **Water use**

The water deprivation potential - deprivation weighted water consumption (WDP) indicator - is quantified by the AWARE model given by Boulay *et al.* (2018). This indicator is quantified based on the relative accessible water remaining per region (or area) when the human and aquatic ecosystems' needs have been complied with. This indicator is expressed in m^3 of world equivalent water deprived.

7.2.2 Additional environmental impact indicators

7.2.2.1 **Particulate matter emissions**

The Particulate matter emissions category is quantified by the potential incidence of disease due to particulate matter emissions (PM) indicator, applying the SETAC-UNEP model described by Fantke *et al.* (2015). This indicator accounts for the adverse effects on human health caused by particulate matter and acidifying substances (NO_X, SO_X and NH_3). This indicator is quantified by the disease incidence caused by particulate matter emissions and acidifying substances, i.e., the number of human diseases caused per kg of particulate matter and acidifying substances emitted.

7.2.2.2 Ionising radiation, human health

This impact category quantifies the Potential Human exposure efficiency relative to U235 (IRP). This quantification is performed by the Human health effect model developed by Dreicer *et al.* (1995), updated by Frischknecht *et al.* (2000). This indicator measures the damage to human health related to the routine releases of radioactive material to the environment and is quantified in relation to the effects of Uranium on human health.

7.2.2.3 Ecotoxicity (freshwater)

This impact category is quantified by the Potential Comparative Toxic Units for ecosystems (ETP-fw) indicator. This indicator was calculated by Usetox version 2 model c. ETP-fw quantifies the impacts of chemical substances on ecosystems (freshwater) and is measured by a comparative toxic unit for ecosystems (CTUe).

7.2.2.4 Human toxicity

The Human toxicity impact category is assessed through two indicators: Potential Comparative Toxic Units for humans - cancer effects (HTP-c), and Potential Comparative Toxic Units for humans - non-cancer effects (HTP-nc). These indicators assess the impacts of chemicals elements on human health (with and without cancerous effects) via air, soil, and water. Both indicators are quantified by using the Usetox version 2 model (Rosenbaum *et al.*, 2008) and measured by a comparative toxic unit for humans (CTUh).

7.2.2.5 Land use related impacts / soil quality

This impact category is quantified by the Potential Soil quality index (SQP) indicator (dimensionless). This indicator is quantified by the Soil quality index provided by the LANCA model (Bos *et al.* (2016)). The LANCA model quantifies five indicators that assess the use of soil: erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration and biotic production.

7.3 Results

The environmental impacts of each level of assessment are shown in Annexes F, G, H and I for forest management, and for production of construction products, building solutions and deck solutions, respectively. This section shows and compares the results of the scenarios described in Section 5, for each level of assessment. The relative environmental impacts were calculated for each category, and their percentage are shown in bar charts in relation to the scenario with the highest impact. The core and additional environmental impact categories are shown separately. Some scenarios had negative impacts on GWP-t and GWP-b categories. This was a consequence of the biogenic carbon sequestered during the growth of trees and its storage in wood products.

7.3.1 Per cubic meter of roundwood (stage A1)

The core and additional environmental impacts of the production of one cubic meter of roundwood under bark (at the forest road) of the various scenarios assessed are shown in Figure 41 and Figure 42, respectively. A further analysis of the influence of forest management operations on environmental impacts is performed in Section 8.1.2.

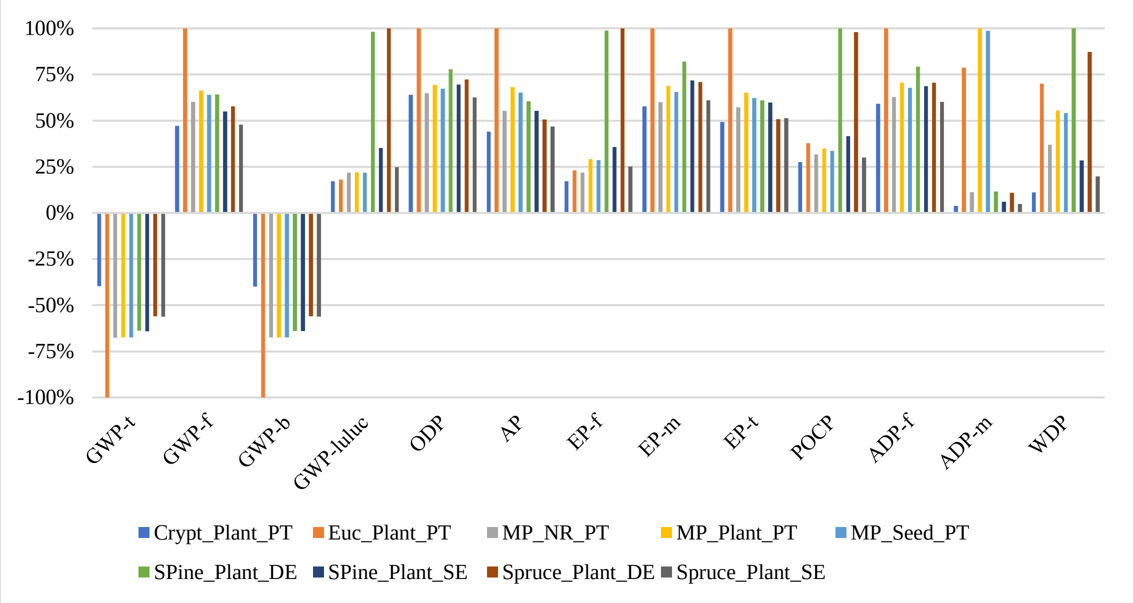

Figure 41 – Relative core environmental impacts per cubic meter of roundwood

In Figure 41, the roundwood of Eucalyptus had the highest impact on the GWP-f, ODP, AP, EP-m, EP-t, and ADP-m categories. In contrast, this scenario had the lowest impact on the GWP-t and GWP-b categories. Spruce from Germany had the highest impacts in GWP-luluc and EP-f categories followed by Scots pine from Germany. Scots pine from Germany had the highest impacts in POCP and WDP, followed by Spruce from Germany. Cryptomeria had the smallest impacts on GWP-f, GWP-luluc, AP, EP-f, EP-m, EP-t, POCP, ADP-m, ADP-f, and WDP. In contrast, Cryptomeria had the highest impact on the GWP-t and GWP-b categories. Maritime pine planted had the highest impacts on the ADP-f category, followed by Maritime pine seeded.

Comparing the Maritime pine scenarios, it can be seen that the natural regeneration scenario had the lowest environmental impact for all the categories assessed, followed by Maritime pine seeded. The planted scenario had the highest environmental impacts on all categories. For Portuguese scenarios, Cryptomeria had the lowest environmental impacts, followed by Maritime pine scenarios for all the categories except for GWP-t and GWP-b, where the Eucalyptus had the lowest impacts. For the German scenarios, Spruce had lower impacts than Scots pine on the GWP-f, ODP, AP, EP-m, EP-t, POCP, ADP-m, ADP-f and WDP categories. For the Swedish scenarios, Spruce had lower impacts than Scots pine on all categories, except for GWP-t and GWP-b.

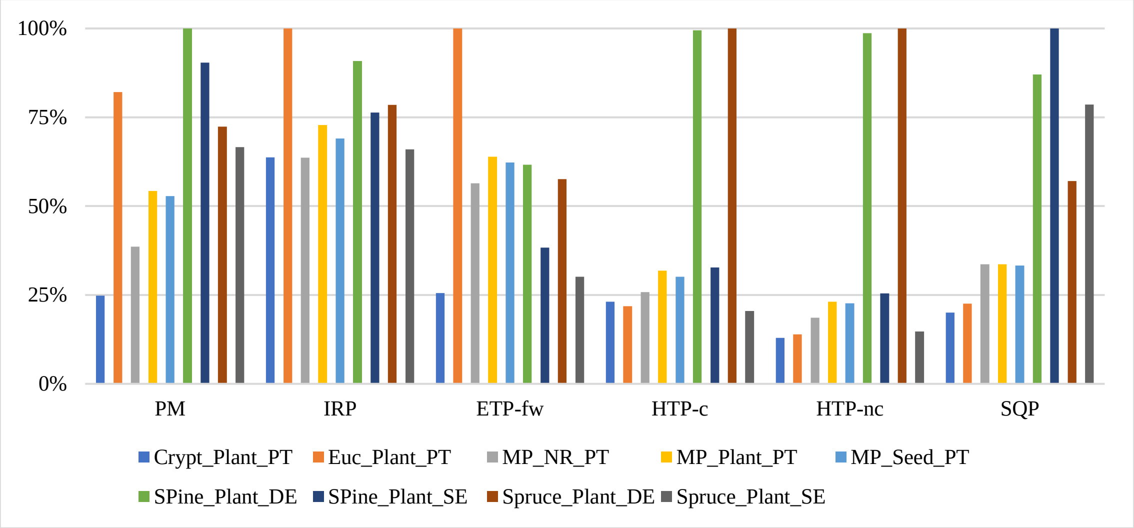

Figure 42 – Relative additional environmental impacts per cubic meter of roundwood

The scenarios with higher impacts in additional environmental categories (Figure 42) were: Eucalyptus in IRP and ETP-fw categories, Spruce from Germany in both HTP categories, Scots pine from Germany in the PM category and Scots pine from Sweden in the SQP category. Cryptomeria had the lowest impacts on all categories, except for the HTP-c category, where the Spruce from Sweden had the lowest impact.

7.3.2 Per cubic meter of structural products (Stages A1-A3)

The results of core and additional environmental impacts of structural products are shown in Figure 43 and Figure 44, respectively. The functional unit is one cubic meter of structural product. The study of the influence of production operations on sawnwood products is performed in Section 8.2.3.

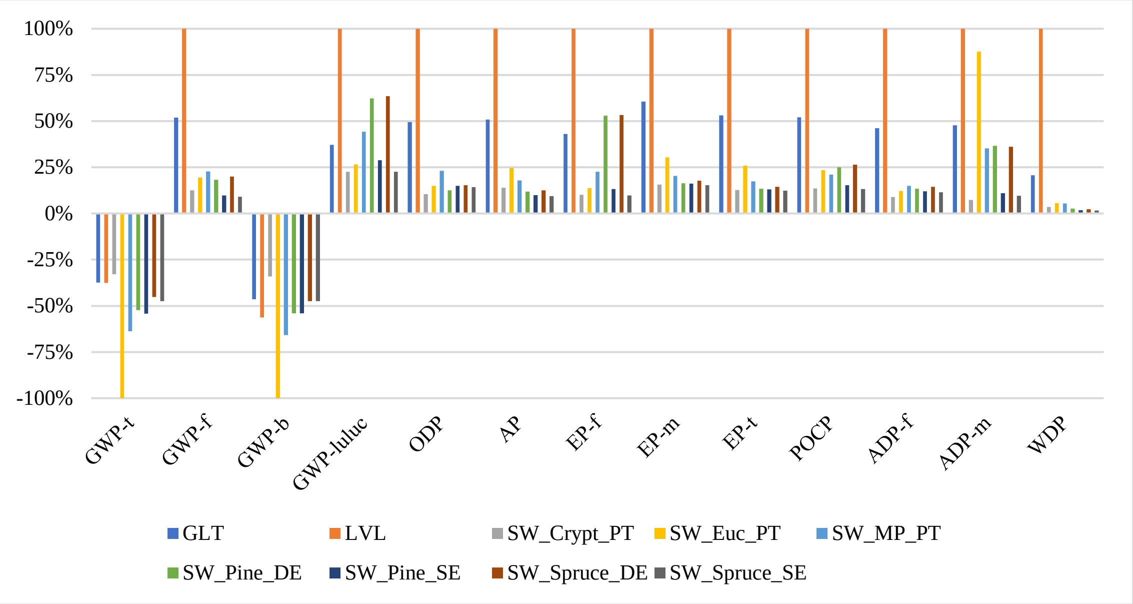

Figure 43 - Relative core environmental impacts per cubic meter of structural products

Figure 43 shows that the product with the highest impacts on all core environmental categories assessed was LVL, except for the GWP-t and GWP-b categories, where Cryptomeria sawnwood had the highest impacts. The GLT scenario had the second highest impacts on GWP-f (51.8%), ODP (49.5%), AP (50.9%), EP-m (60.6%), POCP (52.1%), ADP-f (46.2%), and WDP (20.6%). Spruce sawnwood from Sweden was the scenario that had the lowest impacts on the majority of the impact categories: GWP-f, GWP-luluc, AP, EP-f, EP-m, EP-t, POCP, and WDP. Cryptomeria sawnwood had the lowest impacts on ODP, ADP-m and ADP-f. For GWP-t and GWP-b, Eucalyptus sawnwood had the lowest impacts. Comparing the sawnwood scenarios, Eucalyptus had the highest impacts on the majority of the impact categories: AP (24.7%), EP-m (30.4%), EP-t (25.9%), ADP-m (87.7%), and WDP (5.6%).

Similarly to core environmental impacts, LVL had the highest impacts on all additional categories, except for the SQP category, where GLT had the highest impacts. Maritime pine sawnwood had the lowest environmental impacts on PM and ETP-fw; Spruce from Germany had the lowest impacts on HTP-c and HTP-nc; and Eucalyptus had the lowest impacts on IRP and SQP.

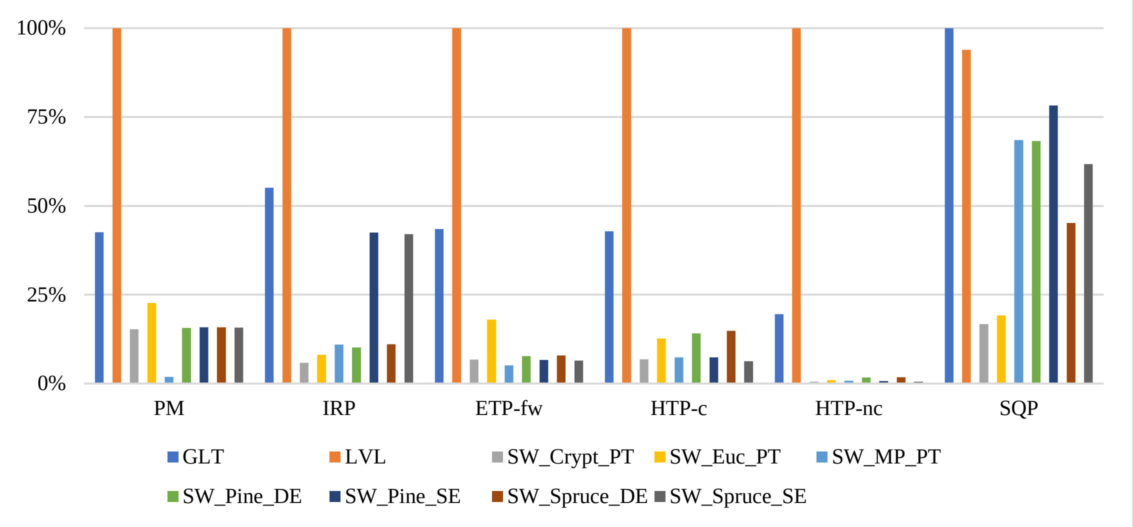

Figure 44 - Relative additional environmental impacts per cubic meter of structural products

A further analysis showed that, for the production of LVL, the operation that had the highest impacts on WDP (76.1%), HTP-c (62.2%), ODP (54.2%), ADP-f (48.9%), GWP-f (46.8%), ADP-m (42.6%), and AP (37.0%) was the UF adhesive production. The PM (88.5%), ETP-fw (81.5%), HTP-nc (60.9%), POCP (51.5%), EP-m (50.9%) impacts of LVL were mainly due to the heat produced for LVL manufacture.

For the GLT scenario, PM (86.4%), ETP-fw (78.1%), HTP-nc (71.4%), EP-m (41.8%), and EP-t (39.9%) impacts were mainly due to the heat produced during GLT and the limited experience of method. GWP-b (97.0%), GWP-t (96.0%), SQP (94.2%), GWP-luluc (62.4%), ODP (51.8%), GWP-f (43.6%), and POCP (42.3%) impacts were mainly due to the sawnwood production operations. WDP (75.1%) and HTP-c (56.0%) were mainly due to the UF adhesive production.

7.3.3 Per equivalent functional unit – residential floor

The environmental impacts of the residential floor case study were determined by calculating the volume of structural products required to fulfil the same structural requirements. The volume for each scenario was determined in Section 4.4 and was multiplied by the environmental impact per cubic meter of product (or linear meter in case of I-Joists). The strength classes of each scenario were those determined by the visual grading methodology given in Section 4.2.1.

The environmental impacts of various scenarios are compared in this section for stages A1-A5 and C1-C4, and assuming different end-of-life scenarios (landfill and incineration). The environmental impacts of the OSB panel used for load distribution were summed to the environmental impacts of each scenario.

7.3.3.1 **Stage A1-A5**

The core and additional environmental impacts of the sum of production and construction stages of structural scenarios are shown in Figure 45 and Figure 46, respectively.

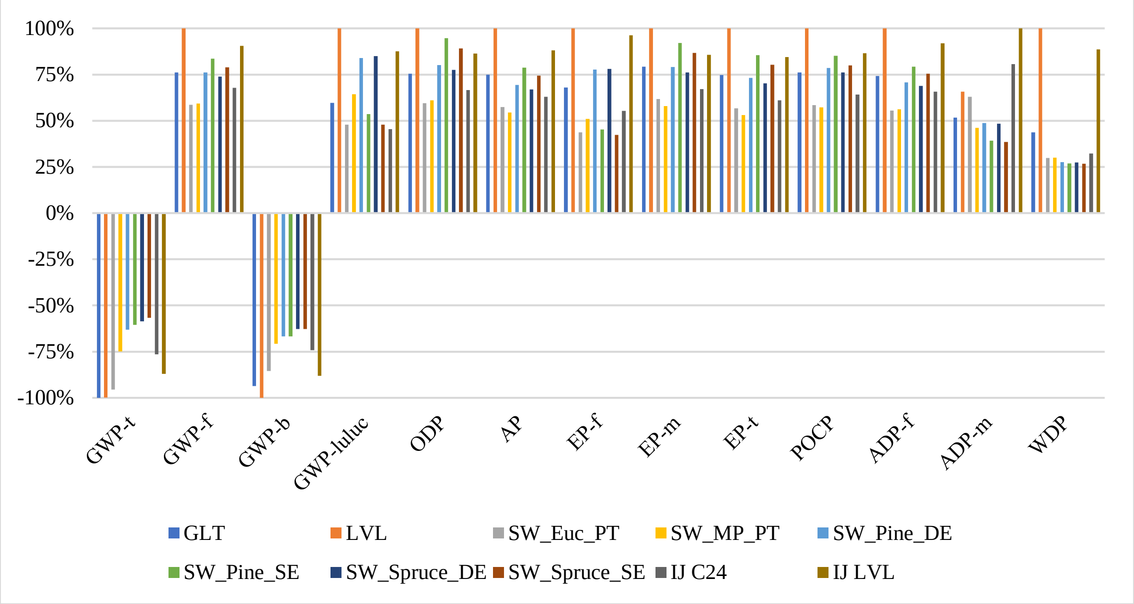

Figure 45 - Relative core environmental impacts of stages A1-A5 per equivalent functional unit of building solution

According to Figure 45, LVL was the scenario that had the highest environmental impacts on all categories, except for: GWP-t and GWP-b, where the Spruce from Sweden had the highest impacts, and ADP-f, where the scenario of I-Joist made with LVL and OSB had the highest impacts. Maritime pine had the lowest impacts on AP, EP-m, EP-t, and POCP categories. Spruce from Sweden had the lowest impacts on the EP-f, ADP-f, and WDP categories and Eucalyptus on ODP, GWP-f, and ADP-m.

Comparing the sawnwood scenarios, Scots pine from Sweden had the highest impacts on all categories, except for GWP-luluc and EP-f, and ADP-f and WDP, where the Spruce from Germany and Eucalyptus had the highest impacts, respectively. Comparing I-Joists environmental impacts, I-Joists made of LVL had the highest impacts on all categories, except for GWP-t and GWP-b categories.

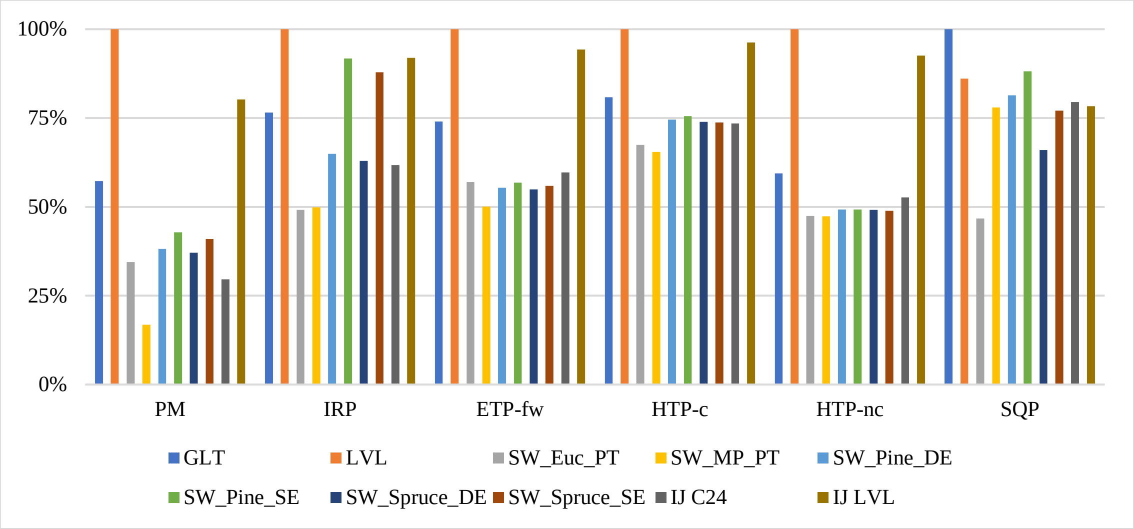

Figure 46 - Relative additional environmental impacts of stages A1-A5 per equivalent functional unit of building solution

In Figure 46, it can be seen that, for additional environmental categories, LVL had the highest impacts on all categories except for the SQP scenario, where the GLT scenario had the highest impacts. Maritime pine sawnwood had the lowest impacts on all categories, except for IRP and SQP, where the Eucalyptus had the lowest scenarios. Comparing the Sawnwood scenarios, Scots pine from Sweden had the highest impacts on all categories.

I-joists made with LVL had higher impacts than I-joists made with sawnwood on all categories, except for the SQP category. Analysing the impacts of I-joist made with LVL, it was found that LVL production had the highest influence on all categories, except for ADP-m, where the OSB production had the highest impacts (57.3%). For I-Joists made with C24 wood, Sawnwood production had the highest impacts on all categories, except for HTP-c, ADP-m, HTP-nc, and WDP categories, where the OSB production had the highest impacts.

7.3.3.2 **Stages C1- C4**

The end-of-life of structural alternatives considered two different scenarios: incineration and landfill. This section compares the core and additional environmental impacts of both scenarios for the various structural solutions assessed.

7.3.3.2.1 Incineration

The core and additional impacts of the end-of-life scenario that considered the incineration of wooden products are shown in Figure 47 and Figure 48, respectively.

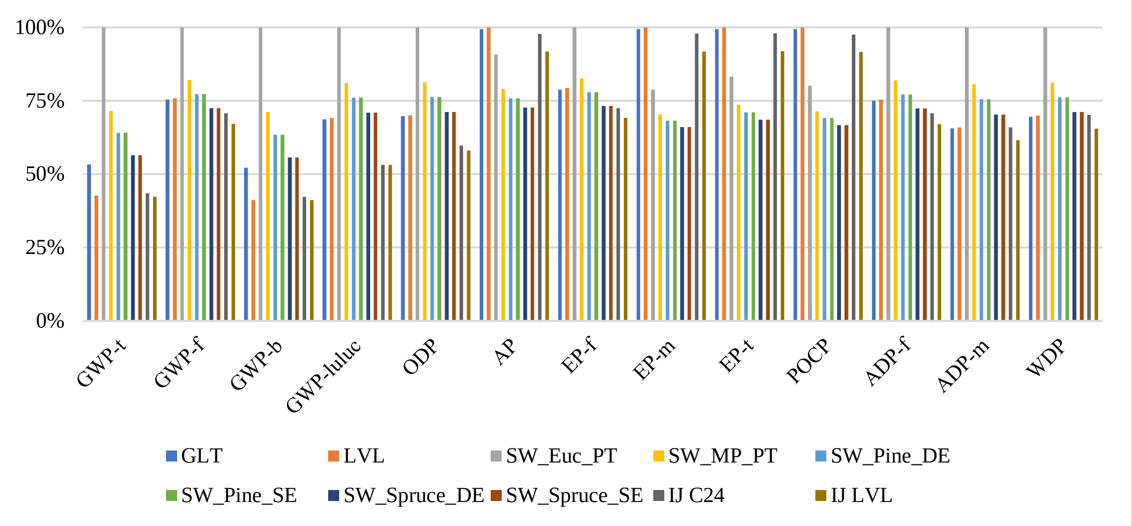

Figure 47 - Relative core environmental impacts of stages C1-C4 per equivalent functional unit of building solution for incineration end-of-life scenario

As seen in Figure 47, the Eucalyptus sawnwood had the highest impacts on all categories, except for AP, EP-m, EP-t, and POCP, where the LVL scenario had the highest impacts. IJ made with LVL had the lowest environmental impacts on the majority of the categories, except for the AP, EP-m, EP-t and POCP categories, where the Spruce scenarios had the highest impacts. The relative impacts are similar for GWP-t, GWP-f, GWP-b, GWP-lu-luc, ODP, EP-f, ADP-m, ADP-f and WDP, and for AP, EP-m, EP-t and POCP, for the alternatives assessed. Scots pine and Spruce results were similar for all the environmental categories assessed.

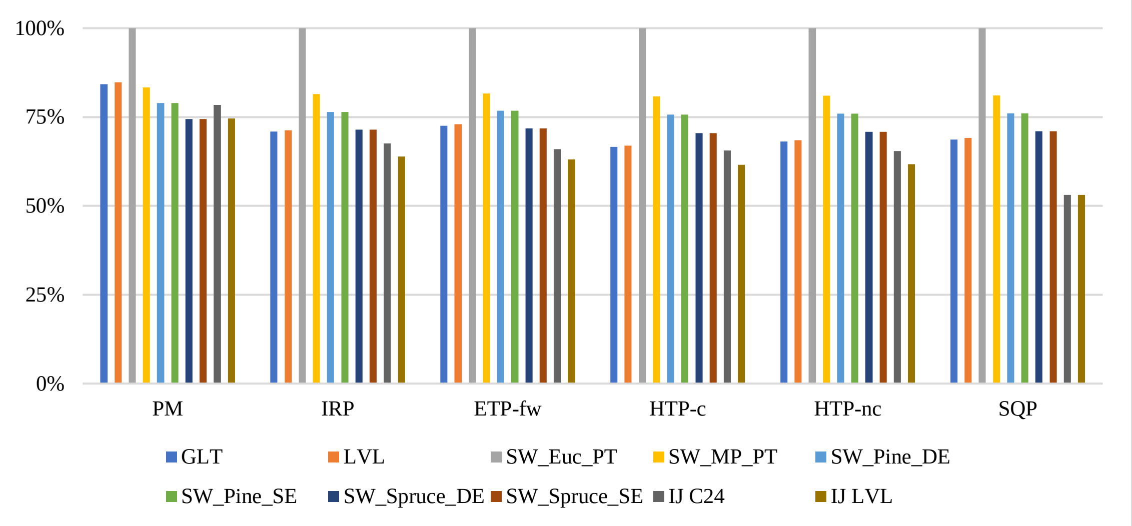

Figure 48 - Relative additional environmental impacts of stages C1-C4 per equivalent functional unit of building solution for incineration end-of-life scenario

For all the additional environmental categories, the scenario that uses the Eucalyptus sawnwood had the highest impacts. I-Joists made with LVL had the lowest environmental impacts on all categories, except for PM, where the Spruce scenarios had the lowest impacts. Scots pine and Spruce results were similar for all the environmental categories assessed. The relative impacts of all the additional categories are similar for all the alternatives assessed.

7.3.3.2.2 Landfill

The core and additional impacts of landfill of wooden products at their end-of-life are shown in Figure 49 and Figure 50, respectively.

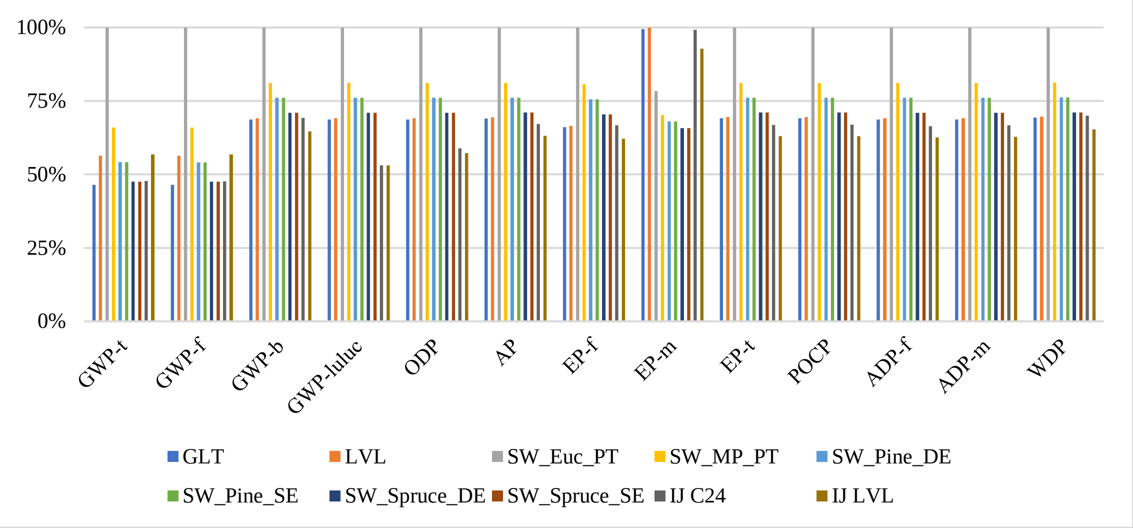

Figure 49 - Relative core environmental impacts of stages C1-C4 per equivalent functional unit of building solution for landfill end-of-life scenario

Figure 49 shows that Eucalyptus sawnwood had the highest impacts on all categories, except for EP-m, where LVL had the highest impact. I-joists made with LVL had the lowest impact on all categories, except for EP-m, where the Spruce scenarios had the lowest impact. All the categories, except GWP-luluc, ODP and EP-m, showed similar results. For the majority of the categories, GLT and LVL showed similar results. For sawnwood, Eucalyptus showed the highest impacts on all categories, followed by Maritime pine. Spruce from Sweden and Germany had the lowest impacts on all categories, followed by Scots pine from both countries.

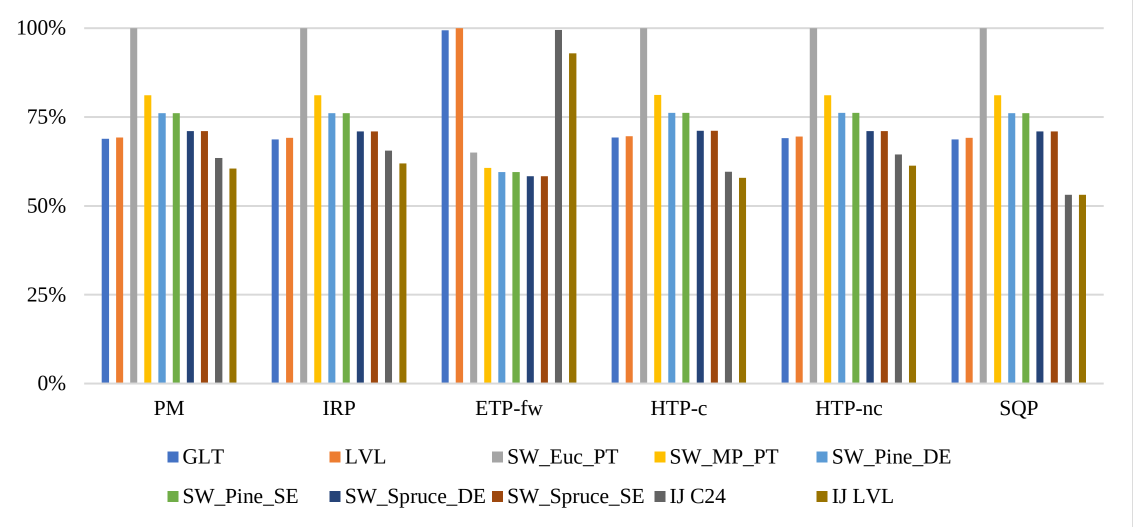

Figure 50 - Relative additional environmental impacts of stages C1-C4 per equivalent functional unit of building solution for landfill end-of-life scenario

For additional environmental indicators, it can be seen that the Eucalyptus scenario had the highest impacts on all categories, except for ETP-fw, where LVL had the highest impacts. I-joist made with LVL shows the lowest environmental impacts on all categories, except for ETP-fw, where Spruce scenarios had the lowest environmental impacts.

Comparing both scenarios (incineration and landfill), incineration had higher impact than landfill on GWP-t, GWP-b, EP-t, ADP-m, WDP, HTP-c and HTP-nc categories for all scenarios. For AP, POCP, and PM categories, incineration had higher impact than landfill on GLT, LVL and I-Joist solutions.

7.3.3.3 **Full life cycle**

This section shows the results of the sum of the environmental impacts of production, construction, and end-of-life stages. As this case study considered two different scenarios for the end-of-life of wooden products, the results of the full life cycle are shown separately for each of these scenarios. The results of the full life cycle with incineration and landfill at the end-of-life are shown in Sections 7.3.3.3.1 and 7.3.3.3.2, respectively.

7.3.3.3.1 Life cycle with incineration

The core and additional life cycle impacts of the entire life cycle with incineration at the end of life are shown in Figure 51 and Figure 52, respectively.

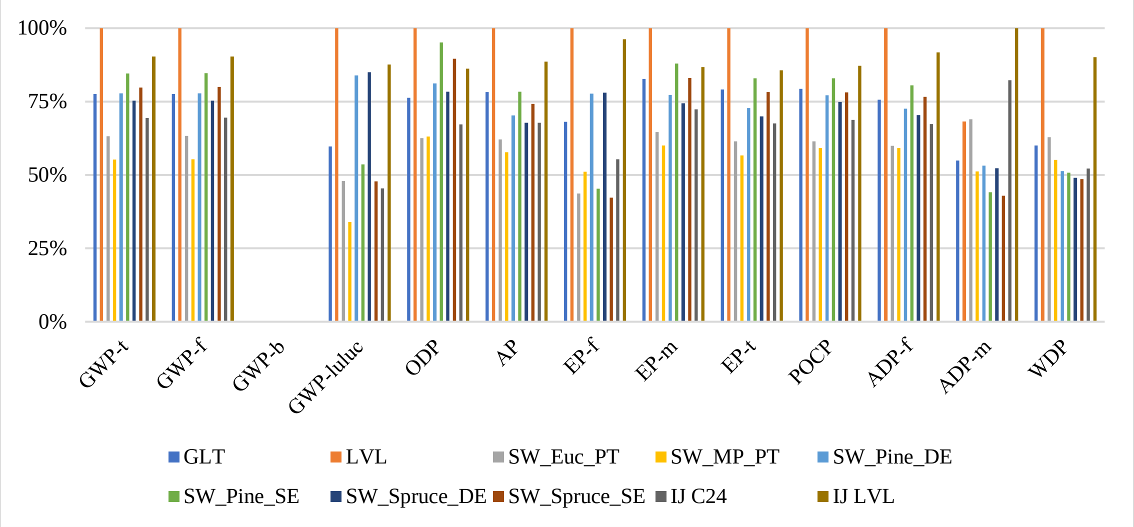

Figure 51 - Relative core environmental impacts of full life cycle per equivalent functional unit of building solution for incineration end-of-life scenario

Figure 51 shows that LVL had the highest environmental impacts on all categories, except for ADP-m, where I-Joists made with LVL had the highest impacts. Maritime pine sawnwood had the lowest impacts on GWP-t, GWP-f, GWP-luluc, AP, EP-m, EP-t, POCP and ADP-f, and Spruce sawnwood from Sweden had the lowest impacts on the EP-f, ADP-m, and WDP categories. GWP-b impacts were zero for all scenarios because the modelling procedures of end-of-life incineration assumed that the biogenic carbon dioxide retained in all products is emitted during the combustion of wood products.

Comparing the various scenarios of sawnwood, Scots pine from Sweden had the highest impacts on the GWP-f, ODP, AP, EP-m, Ep-t, POCP, and ADP-m categories. Spruce from Sweden had the second highest impacts on those categories. Spruce from Germany had the highest impacts on the GWP-luluc and EP-f categories, and Eucalyptus had the highest impacts on ADP-f and WDP. For the majority of the categories, for Scots pine and Spruce scenarios, Sweden’s scenarios had lower impacts than Germany’s ones. For each country, Scots pine had higher impacts than Spruce for the majority of environmental categories. I-Joist made with LVL had higher impacts than I-joists made with sawnwood on all categories.

Maritime pine sawnwood had the lowest impacts on all additional impact categories, except for SQP, where Eucalyptus sawnwood had the lowest impacts. LVL had the highest impacts on all categories, except SQP, where the GLT had the highest impacts. For sawnwood scenarios, Scots pine from Sweden had the highest impact on all categories, except ETP-fw, where Eucalyptus had the highest impacts.

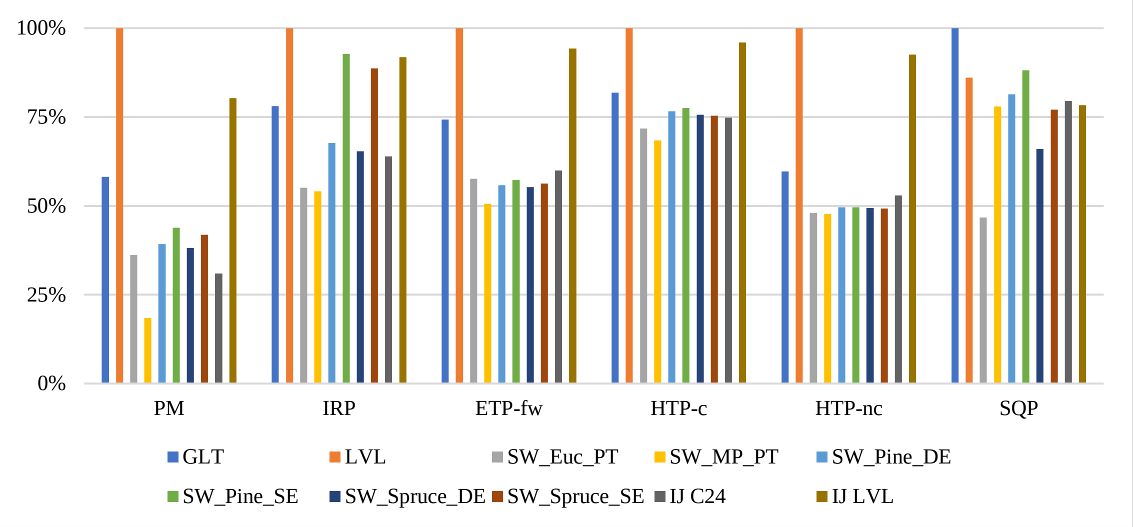

Figure 52 - Relative additional environmental impacts of full life cycle per equivalent functional unit of building solution for incineration end-of-life scenario

7.3.3.3.2 Life cycle with landfill

The core and additional life cycle impact of the entire life cycle of various scenarios that assume landfilling of wood products at their end of life are shown in Figure 53 and in Figure 54, respectively.

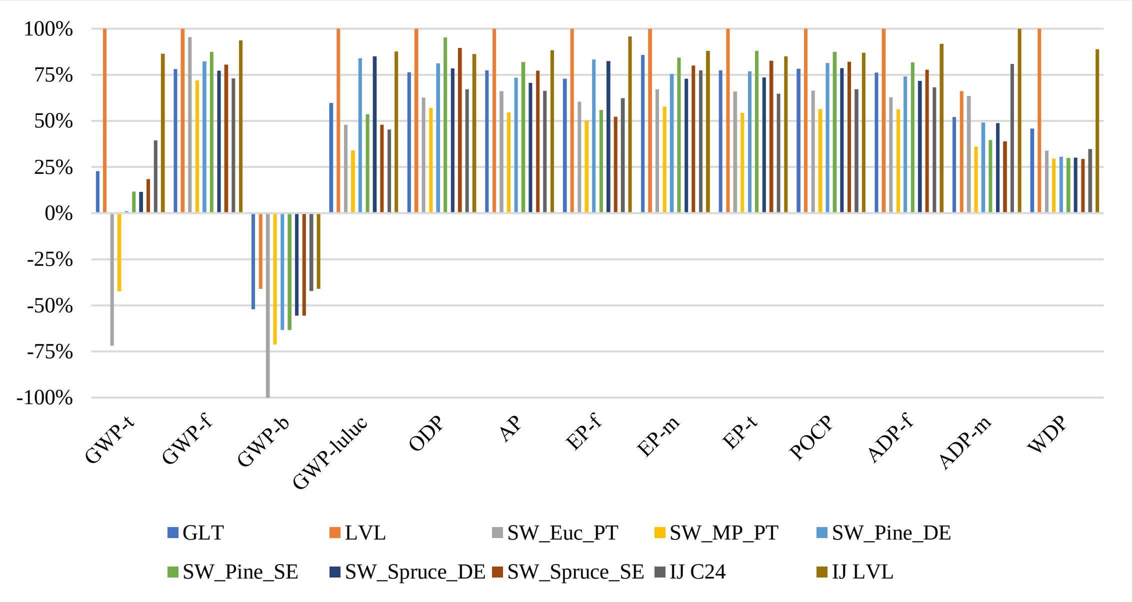

Figure 53 - Relative core environmental impacts of full life cycle per equivalent functional unit of building solution for landfill end-of-life scenario

Figure 53 shows that LVL had the highest impacts on all categories, except for ADP-m, where I-joists made with LVL had the highest impact. Maritime pine sawnwood had the lowest impacts on all categories, except GWP-t and GWP-b, where Eucalyptus sawnwood had the lowest impacts. All the scenarios had a negative impact on the GWP-b category, which means that the carbon dioxide and methane emissions resulting from landfilling of products were lower than the carbon dioxide retained on wood products. Eucalyptus and Maritime pine had negative impacts on the GWP-t category, which means that the amount of carbon dioxide retained in products at their end-of-life was higher than the carbon dioxide and methane emissions during the products' life cycle.

For sawnwood scenarios, Scots pine from Sweden was the scenario that had the highest impacts on the majority of the categories (ODP, AP, EP-m, EP-t, POCP, and ADP-m), followed by the Eucalyptus (GWP-f, ADP-f and WDP). Maritime pine sawnwood had the lowest impacts on the majority of the categories. For Sweden and Germany's scenarios, Spruce had lower impacts than Scots pine on the majority of the categories. I-Joists made with LVL had higher impacts than I-joists made with sawnwood for all the categories.

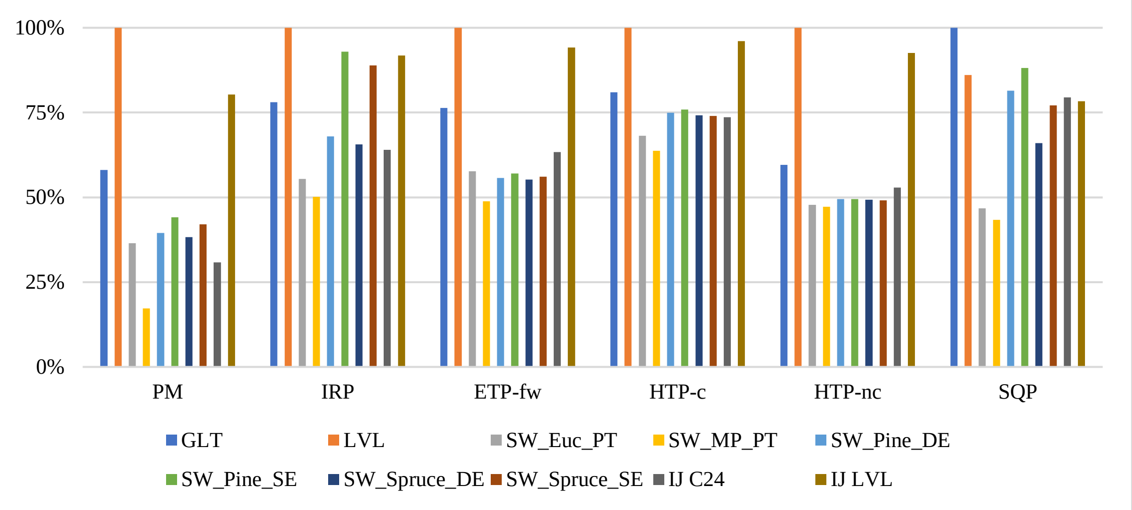

Figure 54 - Relative additional environmental impacts of full life cycle per equivalent functional unit of building solution for landfill end-of-life scenario

Maritime pine sawnwood had the lowest impacts on all additional impact categories. LVL had the highest impacts on all categories, except SQP, where GLT had the highest impacts. For sawnwood scenarios, Scots pine from Sweden had the highest impact on all categories, except ETP-fw, where Eucalyptus had the highest impacts.

Comparing both scenarios, a further analysis found that the landfill scenario had higher impact than the incineration scenario for all products on GWP-t, EP-t, ADP-m, WDP, HTP-c, HTP-nc and SQP categories. However, incineration had a higher impact than landfill for all products in GWP-f, ODP, EP-f, EP-m, and ETP-fw. For other categories, it varied depending on the structural solution. The highest benefit of considering incineration instead of landfill was noted on the GWP-f category (mean of 68.0%), followed by EP-f (mean of 76.5%) and EP-m (mean of 81.9%). In contrast, the highest benefits of considering incineration instead of landfill were noted in the GWP-t category (mean of 9.2%) followed by WDP (mean of 50.7%).

7.3.4 Per equivalent functional unit – deck floor

This section shows and compares the relative environmental impacts of the various scenarios for deck floor described in Section 4.5. These results were compared per life cycle stages: production, use and end-of-life; and for the full life cycle. The various scenarios are compared assuming the same functional equivalence (the number of preservative products and sawnwood required to fulfil the same durability requirements described in Section 4.5).

7.3.4.1 Stage A1-A5

The relative core and additional environmental impacts of the production stages of various durability scenarios are shown in Figure 55 and Figure 56, respectively.

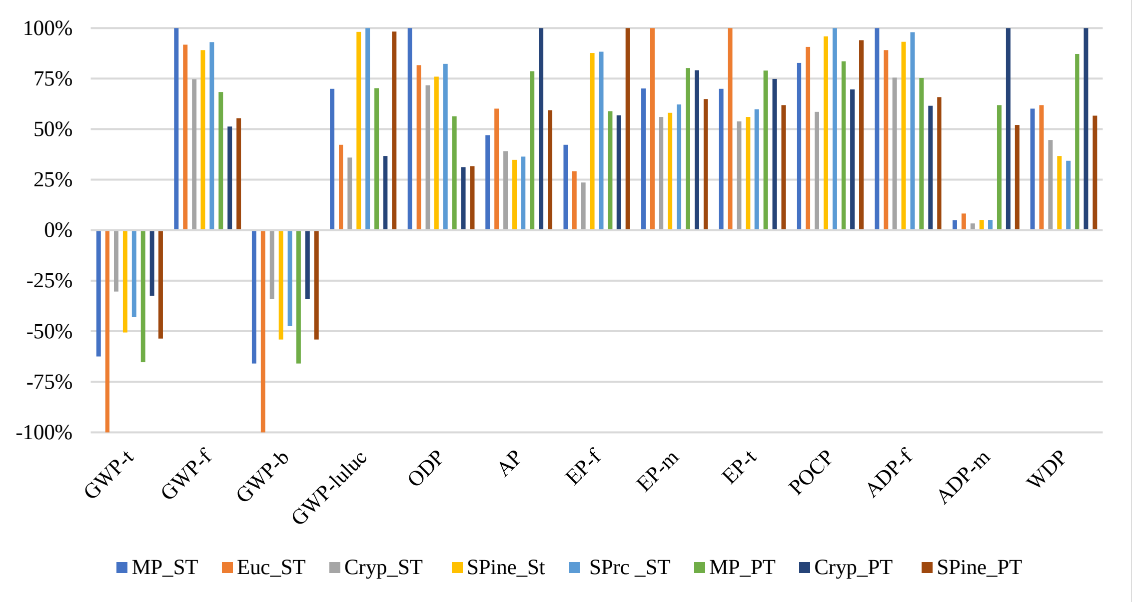

Figure 55 - Relative core environmental impacts of stages A1-A5 per equivalent functional unit of deck solution

Cryptomeria with surface treatments was the scenario that had the lowest impacts on GWP-luluc, EP-f, EP-m, EP-t, POCP, and ADP-m. The same specie with pressurised treatments had the lowest impacts on GWP-f, ODP, and ADP-f. Eucalyptus with surface treatments had the lowest impacts on GWP-t and GWP-b; Spruce with surface treatments had the lowest impacts on WDP, and Scots pine with surface treatments had the lowest impacts on the AP category. Surface treated scenarios had the lowest impacts on all impact categories, except for GWP-f, ODP, and ADP-f categories. A further analysis identified that the operations that had the highest influence on those categories were the emissions during the application of surface treatments.

Cryptomeria treated with pressurised treatment had the highest impacts on the AP, ADP-m and WDP categories and Maritime pine with surface treatments had the highest impacts on GWP-f, ODP and ADP-f. Spruce and Cryptomeria with surface treatments had the highest impacts on GWP-luluc and POCP; and GWP-t and GWP-b, respectively. ADP-m, WDP and AP impacts were higher for pressurised treatments than for surface treatments. A further analysis identified that the highest impacts on these categories are related to the emissions during the production of pressurised treatments. For these categories, the Cryptomeria scenario had the highest impacts, followed by the Maritime pine and the Scots pine's. This is related to the amount of pressurised treatment retained on those species (higher amount of pressurised products means higher impact values).

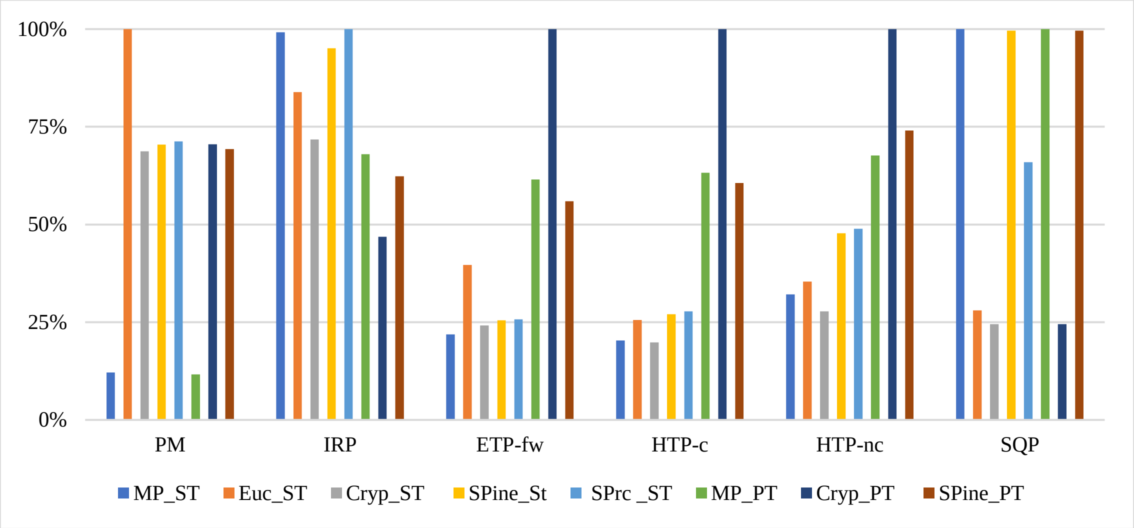

Figure 56 - Relative additional environmental impacts of stages A1-A5 per equivalent functional unit of deck solutions

For additional environmental impacts, Cryptomeria with surface treatment had the lowest impacts on the IRP, HTP-c, HTP-nc, and SQP categories. Maritime pine with surface treatments had the lowest impacts on PM and ETP-fw. Cryptomeria with pressurised treatments was the scenario that had the lowest impacts on the majority of the categories (ETP-fw, HTP-c, HTP-nc, and SQP). Maritime pine scenarios had the lowest impacts on the PM category. On the other hand, Eucalyptus with surface treatment had the highest impacts on this category A further analysis identified that the PM impacts were mainly related to the sawnwood production.

7.3.4.2 **Stages B1-B7**

The results showed that the use phase has no influence on the core environmental impacts and the influence on additional environmental impacts was noted only for ETP-fw and HTP-categories. The additional environmental impacts for ETP-fw and HTP-categories of use phase are shown in Figure 57.

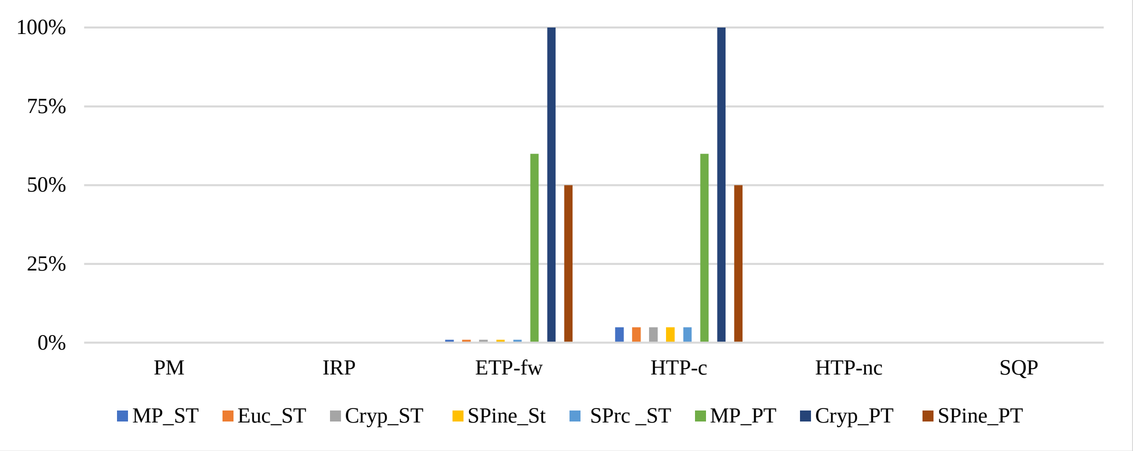

Figure 57 - Relative additional environmental impacts of stages B1-B7 per equivalent functional unit of deck solutions

Figure 57 shows that Cryptomeria with pressurised treatments had the highest impact on both categories assessed. Both pressurised treatment scenarios had the lowest environmental impacts on both categories. For pressurised treatments, the lowest impact was noted for the Scots pine scenario.

7.3.4.3 **Stages C1-C4**

The core and additional environmental impacts of the end-of-life stages of various durability scenarios are shown in Figure 58 and Figure 59, respectively. The comparison of the relative additional and core environmental impacts for the end-of-life scenarios is similar for the majority of the categories and is made jointly in this section.

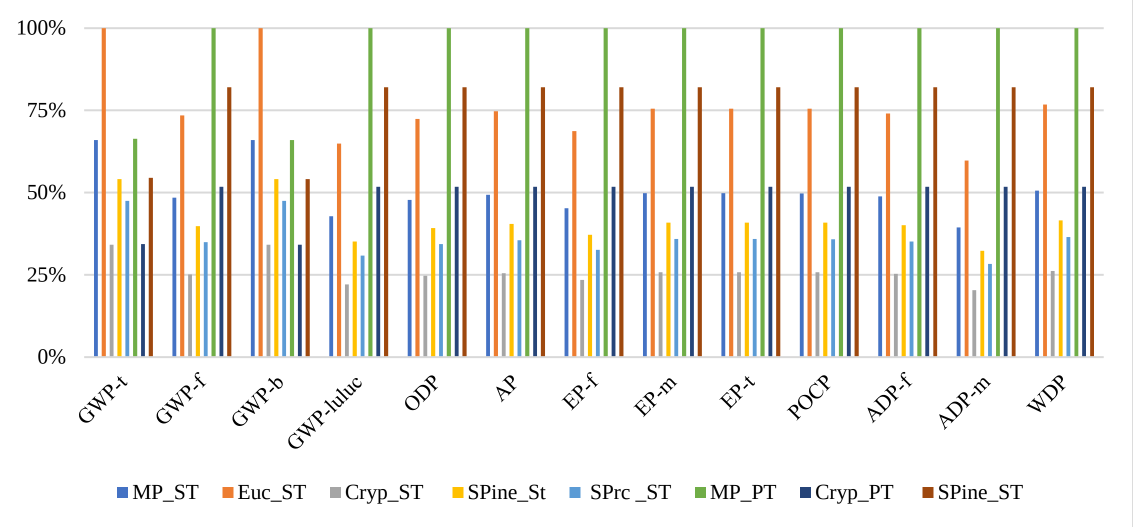

Figure 58 - Relative core environmental impacts of stages C1-C4 per equivalent functional unit of deck solutions

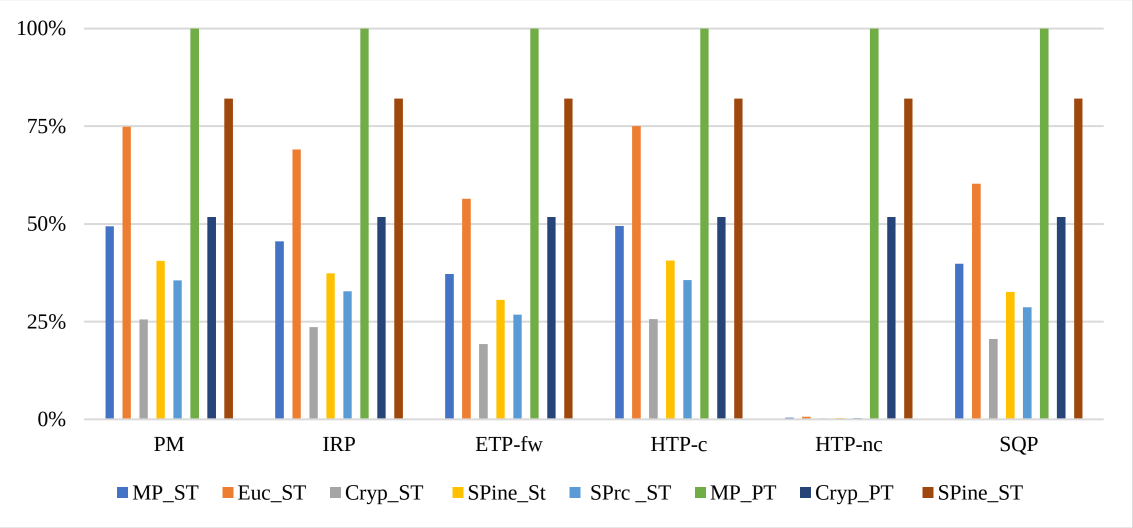

Figure 59 - Relative additional environmental impacts of stages C1-C4 per equivalent functional unit of deck solutions

Maritime pine treated with pressurised treatments was the scenario with the highest impacts on all categories, except for GWP-f and GWP-b, where Eucalyptus with surface treatments had the highest impacts. On the other hand, Cryptomeria with surface treatments had the lowest impacts. Comparing the surface treatments, Eucalyptus had the highest impact on all categories, followed by Maritime pine, Scots pine, Spruce and Cryptomeria. For scenarios with pressurised treatments, Maritime pine showed the highest impacts, followed by Scots pine and Cryptomeria. For the same wood species, pressurised treatments showed the highest impacts. HTP-nc category was the one that showed the highest change of results between pressurised and surface treatments.

7.3.4.4 **Full life cycle**

The core and additional environmental impacts of the stages assessed before are summed up in this section and shown in Figure 60 and Figure 61, respectively.

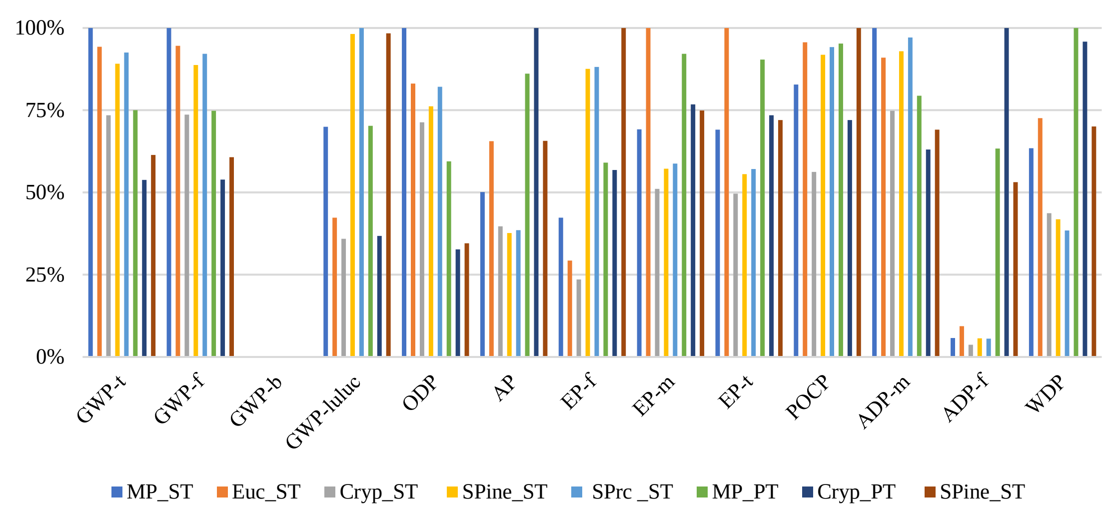

Figure 60 - Relative core environmental impacts of full life cycle per equivalent functional unit of deck solutions

For core environmental impacts, Cryptomeria with surface treatments had the lowest impacts on the majority of the categories (GWP-luluc, EP-f, EP-m, EP-t, POCP, and ADP-f), followed by Cryptomeria with pressurised treatments (GWP-t, GWP-f, ODP and ADP-m). Maritime pine with surface treatments had the highest impacts on the GWP-t, GWP-f, ODP and ADP-m categories.

For additional environmental impacts, Cryptomeria with surface treatment had the lowest impacts on the majority of the impact categories (except for PM and ETP-fw). Cryptomeria with a pressurised treatment had the highest impacts on ETP-fw and HTP-c. For the HTP-nc and SQP categories, the highest impacts were noted for Maritime pine with pressurised treatments.

Comparing the core and additional impacts of surface-treated products, the Cryptomeria scenario had the lowest impacts on the majority of the impact categories. On the other hand, the Eucalyptus scenario had the highest impacts on the majority of the impact categories analysed. For pressurised treatments, Cryptomeria was the scenario that had the lowest impacts on a high number of impact categories, followed by the Scots pine scenario. Maritime pine was the scenario that had the highest impacts on the majority of the categories, followed by the Scots pine scenario. In order to quantify the influence of each life cycle stage on full life cycle impacts, a further analysis is presented in Section 8.4.2 for Maritime pine scenarios.

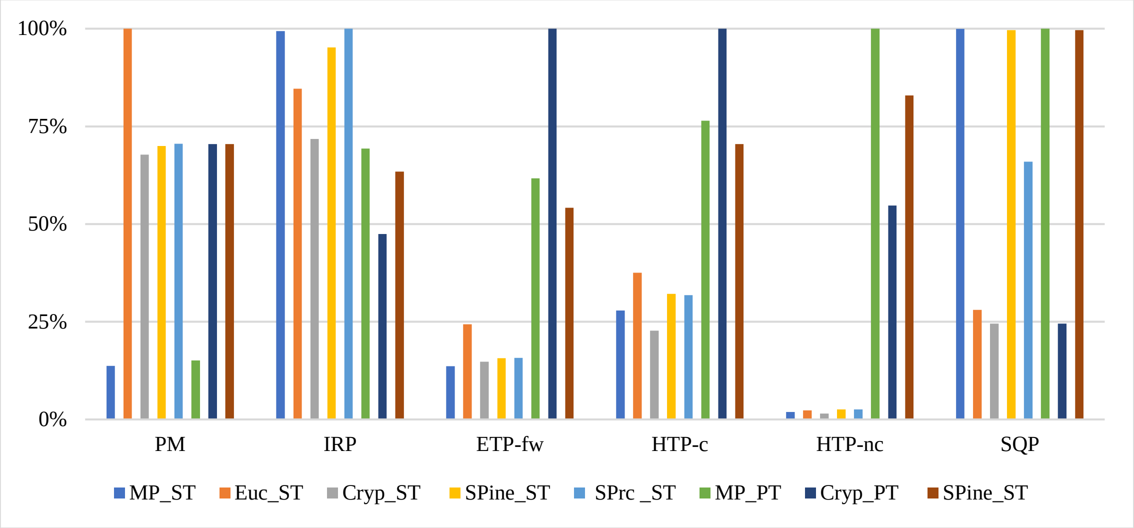

Figure 61 - Relative additional environmental impacts of full life cycle per equivalent functional unit of deck solutions

7.4 Normalisation of results

In order to understand the magnitude of the results of each category indicator, a normalisation of core and additional environmental impacts was performed. The normalization procedure calculates the magnitude of products' environmental impacts in relation to an impact value per year and per person in Europe. The normalization factors considered were those given by the EF3.0 documentation (Fazio *et al.*, 2018) and are shown in Table 64. EN 15804+A2 did not consider this phase. The normalization values were calculated by multiplying the normalisation factors by the environmental impacts in each category.

7.4.1 Roundwood

The roundwood results showed that Eucalyptus was the wood specie with the highest impacts on the majority of the categories assessed. On the other hand, the Cryptomeria wood species had the lowest impacts on the majority of the impact categories. The normalisation of core and additional environmental impacts are shown in Figure 62.

Table 64 – Normalisation factors given by the EF 3.0 methodology

Categories	Normalisation factors
Unit	Person.year
GWP-t	1.24E-04
ODP	1.86E+01
AP	1.80E-02
EP-f	6.22E-01
EP-m	5.12E-02
EP-t	5.66E-03
POCP	2.46E-02
ADP-m	1.57E+01
ADP-f	1.54E-05
WDP	8.72E-05
PM	1.68E+03
IRP	2.37E-04
ETP-fw	2.34E-05
HTP-c	5.92E+04
HTP-nc	4.35E+03
SQP	1.22E-06

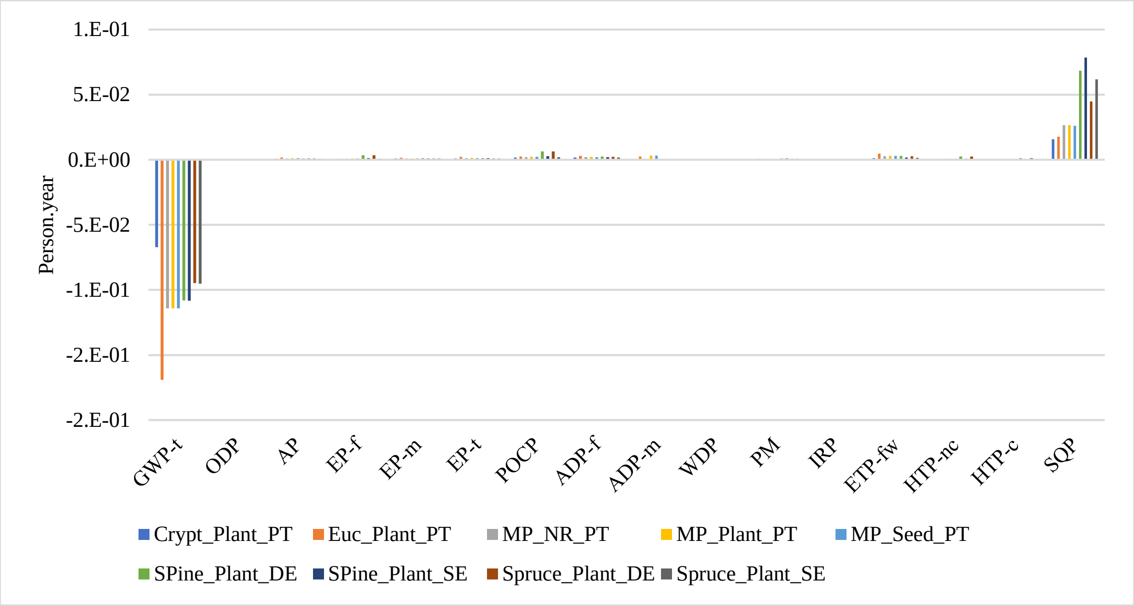

Figure 62 – Normalised environmental impacts of stage A1 per cubic meter of roundwood

As seen in Figure 62, GWP-t was the category with the lowest impacts, followed by SQP. For the GWP-t category, Eucalyptus had the lowest impacts, followed by the Maritime pine, Scots pine and Spruce scenarios. Cryptomeria was the scenario with the highest impact. For the SQP category, the Scots pine scenarios had the highest impacts, followed by Spruce. For these alternatives, Swedish scenarios had higher impacts than German's scenarios.

For the scenarios from the Ecoinvent database compared in Section 7.3.1, German scenarios had a higher impact than Swedish ones for the majority of the categories. This difference was higher for the GWP-luluc, EP-f, POCP, WDP, HTP-c and HTP-n categories. As described in Chapter 6, German scenarios required a higher number of forest operations, hours of work and years of forest management than Swedish ones.

For scenarios inventoried based on companies' inquiries (Cryptomeria, Maritime pine and Eucalyptus), Eucalyptus had the highest impacts for the majority of the categories, followed by the Maritime pine scenarios. Cryptomeria had the lowest impacts on the majority of the environmental categories. To better understand the influence of the operations performed on the results, Chapter 8 quantifies the influence of each forest management operation on results.

The results showed that, for the Maritime pine scenarios, natural regeneration was the scenario with the lowest environmental impacts. This difference was higher (88%) for the ADP-m category. In the ADP-m category, the Eucalyptus, Maritime pine planted, and Maritime pine seeded scenarios had higher impact than the other scenarios (higher than 60%). These scenarios were the only forest management scenarios that considered the fertilising of trees. The influence of fertilising operations on the ADP-m category was already noted by Dias & Arroja (2012).

As seen in Figure 62, GWP-t was the category with the lowest impacts on all scenarios; for that reason, the GWP-t sub impacts are presented in Figure 63.

The impacts of the GWP-t category showed that GWP-b category was the category with the highest influence. For the GWP-b category, Eucalyptus had the lowest impacts, followed by Maritime pine, Scots pine and Spruce. The characterization factors of the EN 15804+A2 (CEN, 2019) methodology showed that the GWP-b impacts are influenced by the amount of biogenic carbon dioxide that was sequestered during the growth of trees. The biogenic carbon sequestered was calculated by EN 16449 (CEN, 2014a) and depends on the dry wood density of wood species. Thus, it can be seen that the biogenic carbon sequestered during the growth of trees has a high influence on the GWP-t environmental impacts of roundwood.

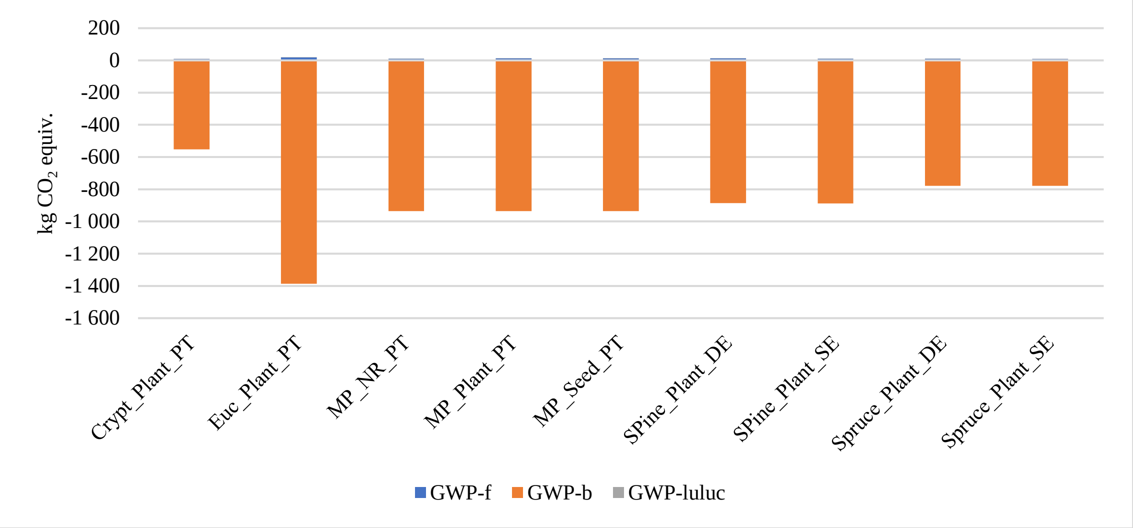

Figure 63 – GWP-f, GWP-b and GWP-luluc environmental impacts of stage A1 per cubic meter of roundwood

7.4.2 Structural products

The results of the comparison of structural products per cubic meter showed that LVL had the highest impacts on the majority of the environmental categories, followed by GLT. Maritime pine sawnwood had the lowest impacts for the majority of the environmental categories. The normalisation of core and additional environmental impacts are shown in Figure 64.

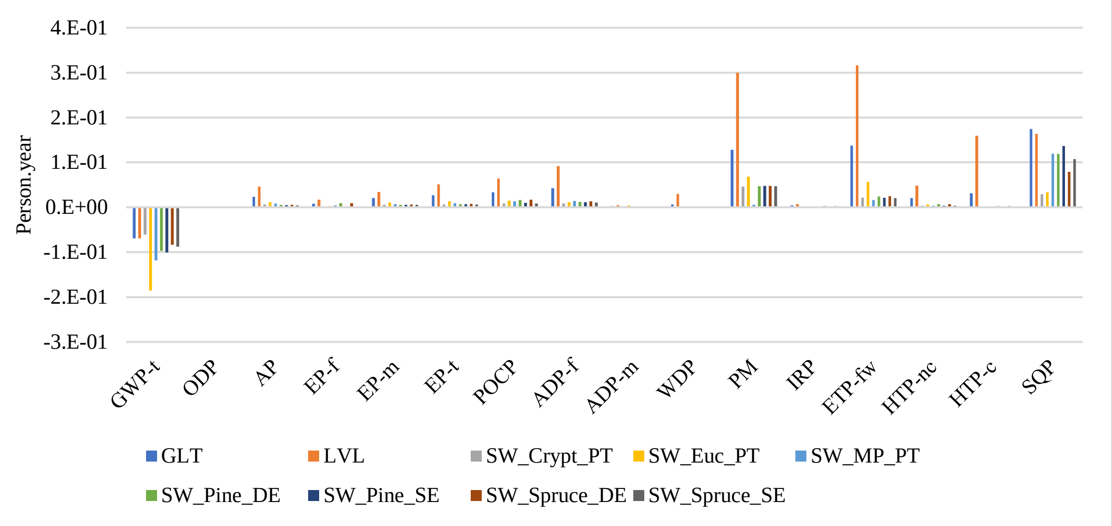

Figure 64 – Normalised environmental impacts of stage A1-A3 per cubic meter of structural products

PM, ETP-fw, SQP, GWP-t and HTP-c were the categories that had the highest normalised impacts. LVL was the scenario that had the highest impacts on the PM, ETP-fw, and HTP-c categories, followed by the GLT scenario. GLT had the highest impact on the SQP category, followed by LVL. Eucalyptus had the lowest impacts on the GWP-t category, followed by the Maritime pine scenario.

The results given in Section 7.3.2 and Figure 64 showed that LVL and GLT were the products with the highest impacts in the majority of the environmental categories. These results are aligned with the ones of Hill and Dibdiakoval (2016), which show that products that require higher manufacturing operations have higher environmental impacts.

7.4.3 Residential floor

For residential floors, the results varied for each life cycle stage. The results are analysed below for a full life cycle for both end-of-life scenarios: incineration and landfill. For the incineration scenario, LVL had the highest impacts on the majority of the categories, followed by I-Joists made with LVL. For the landfill scenario, the results were similar to those for incineration: structural scenarios that used LVL had the highest environmental impacts on the majority of the environmental categories.

The normalisation of the environmental impacts for a full life cycle of a residential floor that considers the incineration and landfill at the end-of-life are shown in Figure 65 and in Figure 66, respectively.

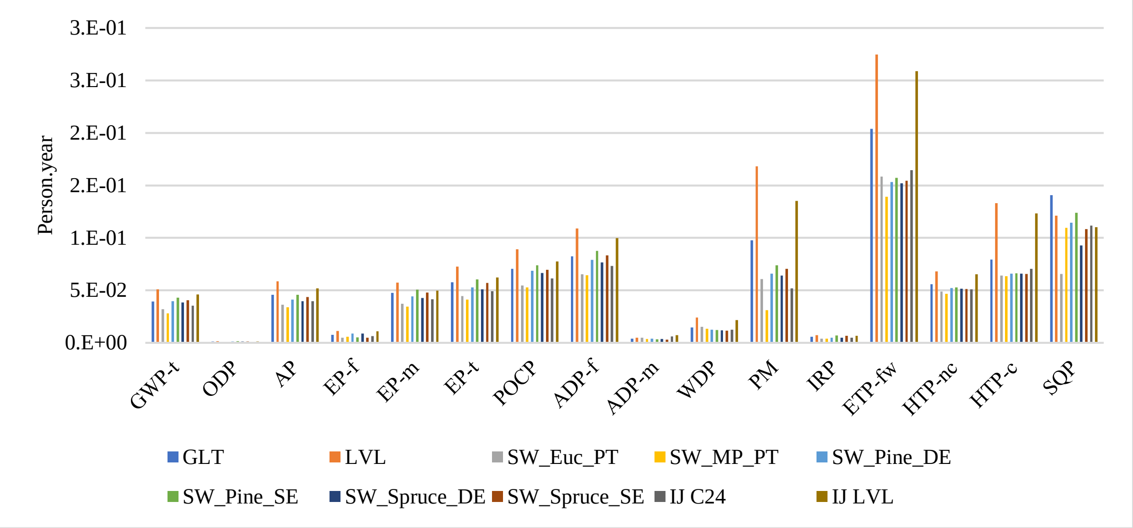

Figure 65 - Normalised environmental impacts of full life cycle with incineration at the end-of-life per structural solution

Figure 65 shows that the highest environmental impacts were noted for ETP-fw, PM, SQP, and HTP-c categories. For the ETP-fw, PM and HTP-c categories, the highest impacts were noted for LVL, followed by I-Joist made with LVL. The lowest impacts were noted for the Maritime pine scenario. The lowest impacts were noted for the ODP, ADP-m, IRP, EP-f and WDP categories.

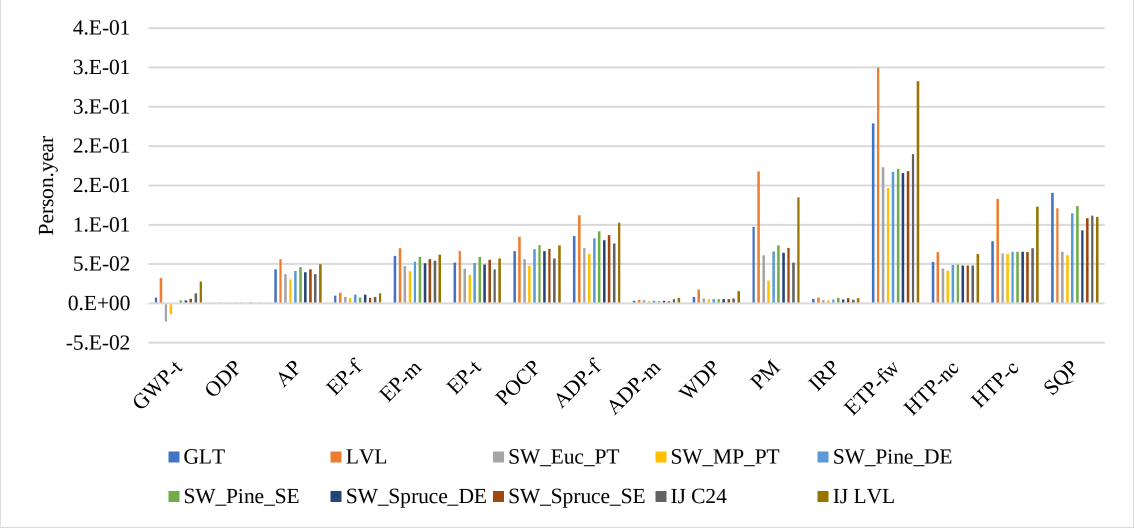

Figure 66 - Normalised environmental impacts of full life cycle with landfilling at the end-of-life per structural solution

For a scenario that considered the landfilling of products, it can be seen that the highest impacts were noted on the ETP-fw, PM, HTP-c and SQP categories. For those categories, LVL had the lowest impacts, except for SQP, where GLT had the highest impacts. I-Joists made with LVL had the second highest impacts on those categories.

Comparing both scenarios (landfilling and incineration), ETP-fw impacts were higher for the landfill scenarios than for incineration ones. PM, HTP-c and SQP impacts were similar for the landfill and incineration scenarios, except for the Maritime pine impacts on the SQP category, which were lower in the landfill scenario.

7.4.4 Deck floor

For deck floors, the results showed that Cryptomeria with penetrating treatments (a scenario with higher preservative product retained) was the scenario with the highest impacts on the majority of the environmental categories, followed by Eucalyptus with surface treatment. The normalised results are shown in Figure 67.

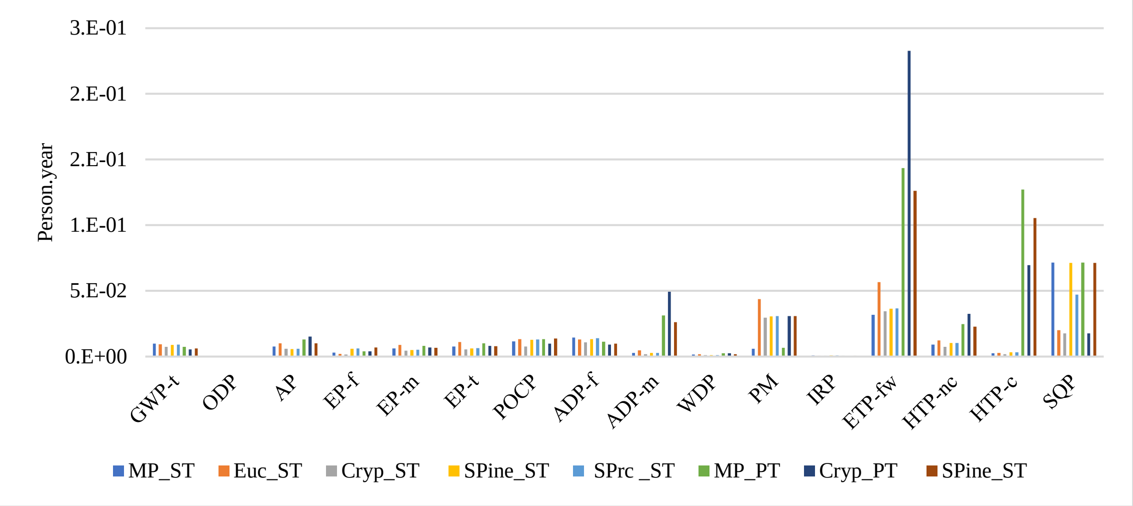

Figure 67 - Normalised environmental impacts of the full life cycle per deck solution

The normalised impacts showed that the highest impacts were noted for ETP-fw, HTP-c, SQP, ADP-m and PM. For ETP-fw and ADP-m, the highest impacts were for Cryptomeria with pressurised treatments, followed by Maritime pine and Scots pine with pressurised treatments. For the HTP-c category, Maritime pine treated by pressurised treatments had the highest impacts, followed by Scots pine and Cryptomeria with the same treatment method. For the SQP scenario, the Maritime pine and Scots pine scenarios had the highest impacts. For PM, the highest impacts were registered by the Eucalyptus scenario with surface treatments.

7.5 **Conclusions**

This chapter describes the LCIA methodology used to calculate the environmental impacts and compares the core and additional environmental impacts of various levels of assessment. Additionally, the normalised impacts were compared. The LCIA methodology used in this study was that proposed by EN 15804+A2 (CEN, 2019).

The environmental categories were divided into core (11 categories) and additional categories (6 categories). The core environmental categories are: GWP-t, GWP-f, GWP-b, GWP-luluc, ODP, AP, EP, POCP, ADP-m, ADP-f, and WDP; and additional environmental categories are: PM, IRP, ETP-fw, HTP-c, HTP-nc, and SQP.

The comparison at the forest management level showed that Cryptomeria had the lowest impacts on the majority of the impact categories. Eucalyptus had the highest impacts on the majority of the impact categories, followed by Swedish scenarios (Scots pine and Spruce). For Maritime pine scenarios, the natural regenerated forest management scenario was the one that had the lowest impacts. On the other hand, planted Maritime pine had the highest impacts.

The comparison of structural products showed that LVL was the structural product that had the highest impacts on the majority of the impact categories, followed by GLT. Spruce sawnwood from Sweden was the scenario that had the lowest impacts on the majority of the impact categories. Cryptomeria sawnwood was the Portuguese scenario that had the lowest impacts on the majority of the impact categories. On the other hand, Eucalyptus was the Portuguese scenario that had the highest impacts on the majority of the impact categories.

For the production and construction stages (A1-A5) of residential floor solutions, LVL had the highest impacts followed by IJ made with LVL. Maritime pine sawnwood was the scenario that had the lowest impacts on the majority of the impact categories. For end-of-life stages (C1-C4), for the incineration scenario, Eucalyptus had the highest impacts on the majority of the impact categories. IJ made with LVL had the lowest impacts on the majority of the categories. The results were similar for the landfill scenario. During the entire life cycle, LVL and Maritime pine showed the highest and the lowest impacts on the majority of the impact categories, respectively.

For durability solutions, the results showed a high variability between life cycle stages. For the entire life cycle, Cryptomeria with surface treatments had the lowest impacts on the majority of the categories, followed by Cryptomeria with pressurised treatments. Maritime pine with surface treatments had the highest impacts on the majority of the impact categories.

The normalisation of results found that, for roundwood, the highest impacts were noted for the GWP-t and SQP categories. For structural products, the highest impacts were noted for the GWP-t, SQP, ETP-fw and PM categories. For the residential floor, the highest impacts were noted for the ETP-fw, PM, SQP and HTP-c categories. For the deck floor, the ETP-fw, HTP-c and SQP categories had the highest impacts.

8 INTERPRETATION

This chapter presents the interpretation stage of the LCA methodology. The interpretation carried out intended to perform completeness, sensitivity, and consistency analysis in order to provide reliable conclusions, consistent recommendations and identify the study's limitations. The assessments performed were based on the alternative scenarios identified during the goal and scope definition, LCI, and LCIA stages.

8.1 **Roundwood**

8.1.1 Comparison of results with literature review results

Some studies identified in the literature review compared the environmental impacts of Maritime pine and Eucalyptus roundwood (Dias & Arroja, 2012; Ferreira *et al.*, 2021). Dias & Arroja (2012) calculated and compared the environmental impacts of various Portuguese forest management scenarios for Maritime pine and Eucalyptus. For each wood specie, three scenarios were considered (1MP, 2MP, and 3MP for Maritime pine and 1E, 2E, and 3E for Eucalyptus), which varied the intensity of the operations performed during the growth of trees, being 1MP and 1E the scenarios with the highest intensity. The environmental impacts were calculated using the CML 2001 methodology (Guinee, 2002).

The results of Dias & Arroja (2012) were compared with the results obtained in this study for Maritime pine and Eucalyptus scenarios. The relative environmental impacts are shown in Table I-1 of Annex I and compared in Figure 68. The environmental impacts of Maritime pine and Eucalyptus scenarios assessed in this study were recalculated for this comparison using the CML 2001 methodology (Guinee, 2002).

The scenario with the highest impacts in all environmental categories assessed was 1E, except for POCP, where the MP_Plant_PT scenario had the highest impacts. The 3MP scenario had the lowest impacts on all categories, except for POCP, where the 1MP scenario had the lowest impacts.

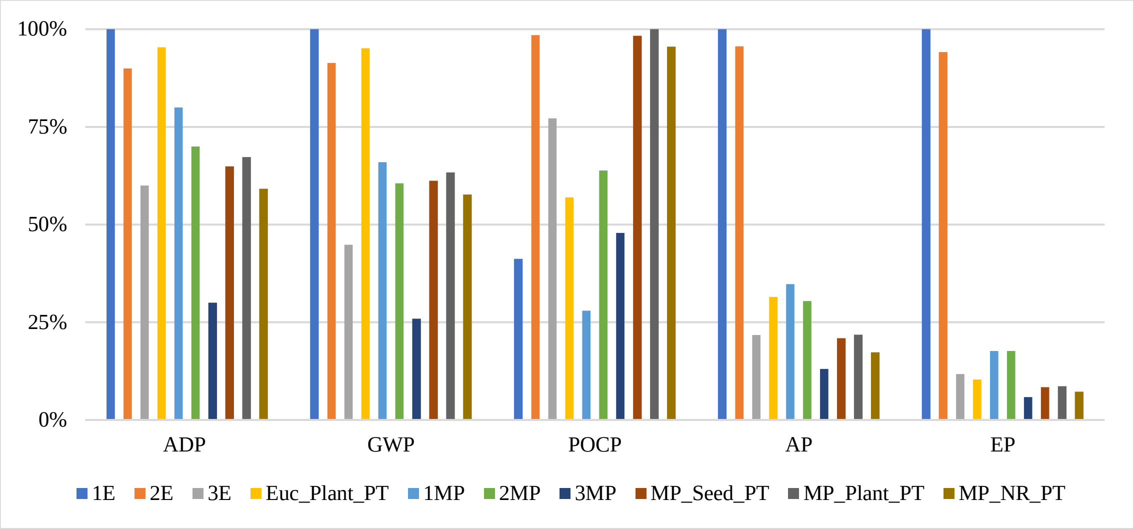

Figure 68 – Comparison of relative environmental impacts of Eucalyptus and Maritime pine roundwood scenarios of this study with literature review (Dias & Arroja, 2012)

For the ADP and GWP categories, the Euc_Plant_PT scenario had similar results to the 1E and 2E scenarios. The 1E and 2E scenarios had a greater impact on the AP and EP environmental categories than the other scenarios. According to Dias & Arroja (2012), this is related with the impacts of the use of fertilizers. For each cubic meter of roundwood, 1E and 2E consume 2,075.0 g and 1,250.0 g and Euc_Plant_PT consume 564.5 g and 241.9 g of P- and N-containing fertilizers, respectively. For the ADP, GWP, AP and EP categories, the MP_Seed_PT, MP_Plant_PT, and MP_NR_PT scenarios had similar impacts to the 1MP and 2MP scenarios. For these categories, the 1MP and 2MP scenarios had higher impacts than the MP_Seed_PT, MP_Plant_PT, and MP_NR_PT scenarios, and 3MP had lower impacts than the MP_Seed_PT, MP_Plant_PT, and MP_NR_PT scenarios.

Analysing the results from Dias & Arroja (2012), it can be seen that the scenarios with the highest intensity had the highest impacts in the majority of the environmental categories, except for POCP, where the 1E and 1MP scenarios had the lowest impacts. This was a consequence of the differences between the machinery used in higher intensity scenarios (harvester) and lower and medium intensity scenarios (chainsaw). For Portuguese forest scenarios inventoried in this study, the influence of each stage of forest operations on environmental categories is discussed on Section 8.1.2.

Ferreira *et al.* (Ferreira *et al.*, 2021) calculated the environmental impacts of 1 cubic meter of roundwood of Maritime pine. The results obtained in that study are compared with the results from MP_Seed_PT, MP_Plant_PT, and MP_NR_PT scenarios: the environmental impacts are shown in Table I.2 of Annex I and compared in Figure 69. For this comparison, the environmental impacts of this study were recalculated using the same LCIA method used by Ferreira *et al.* (Ferreira *et al.*, 2021) - CML-IA (baseline) V3.05/World 2000 methodology (Guinee, 2002).The categories assessed were: abiotic depletion non fossil fuels (ADP-m); Abiotic depletion - fossil fuels (ADP-f); global warming (GWP); ozone layer depletion (ODP); human toxicity (HTP); fresh water aquatic ecotoxicity (EcoTox-fw); marine aquatic ecotoxicity (EcoTox-m); terrestrial ecotoxicity (EcoTox-t); photochemical oxidation (POCP); acidification (AP); and eutrophication (EP).

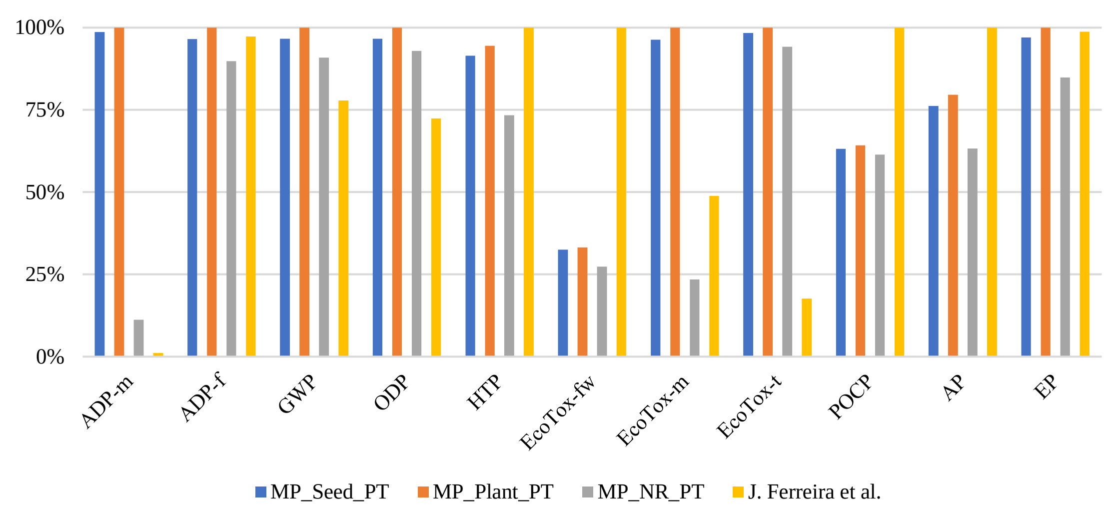

Figure 69 - Comparison of relative environmental impacts of Maritime pine roundwood scenarios of this study with literature review (Ferreira *et al.*, 2021)

Figure 69 shows that the results were similar between both studies. MP_Plant_PT scenario had the highest impacts on the ADP-m, ADP-f, GWP, ODP, EcoTox-m, EcoTox-t and EP categories, and the scenario modelled by Ferreira *et al.* (2021) had the highest impacts on the HTP, EcoTox-t, EcoTox-fw, POCP and AP categories. MP_NR_PT was the scenario with lowest impacts on ADP-f, HTP, EcoTox-fw, EcoTox-m, POCP, AP, and EP. For the ADP-m category, the scenario modelled by Ferreira *et al.* (Ferreira *et al.*, 2021) had an impact significantly lower than MP_Seed_PT and MP_Plant_PT scenarios. For this category, the results were mainly influenced by the extraction of zinc to produce fertilizers that are used on MP_Seed_PT and MP_Plant_PT scenarios.

8.1.2 Life cycle impacts per operation

In order to identify the hotspots of the production of roundwood, the environmental impacts of the following operations were considered: i) site preparation, ii) stand establishment and tending, iii) logging operations and iv) wood and land use (properties inherent to wood species and land use) for inventoried scenarios. The percentage of each operation is shown in Figure 70 to Figure 74 for Crypt_Plant_PT, Euc_Plant_PT, MP_Plant_PT, MP_NR_PT, and MP_Seed_PT, respectively. For all scenarios, the wood inherent properties and land use represent the totality of GWP-b and SQP categories. For the other categories (except for GWP-t), the influence of wood inherent properties and land use was 0%.

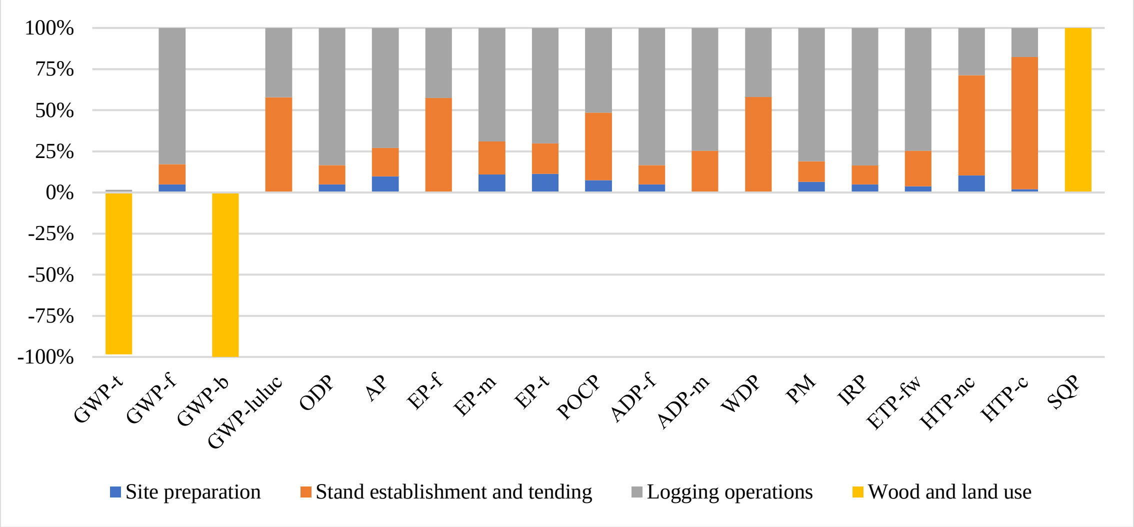

Figure 70 – Comparison of environmental impacts per forest management operation of Crypt_Plant_PT scenario

For the Crypt_Plant_PT scenario, shown in Figure 70, logging operations had the highest influence on the GWP-f, ODP, AP, EP-m, EP-t, POCP, ADP-f, ADP-m, PM, IRP, and ETP-fw categories. Stand establishment and tending had the highest influence on the GWP-luluc, EP-f, HTP-c and HTP-nc categories. Site preparation operations had the lowest influence on the environmental impacts.

The environmental impacts of the GWP-t category were highly influenced by the GWP-b environmental impact, which is influenced by the carbon dioxide captured during the growth of trees. Logging operations (delimbing (44.3%) and harvesting (31%)) had the highest influence on the GWP-f category due to the carbon dioxide (fossil) emissions to the air, resulting from the petrol combustion.

ODP and IRP indicators showed a high influence of logging operations because of the emissions of Halon 1301 to the air, resulting from petrol production. The high influence of logging operations on the AP indicator was a consequence of NOx and SO emissions to the air because of diesel combustion during delimbing (37.9%) and harvesting (27.5%) operations.

EP-m and EP-t indicators showed similar percentages of influence of operations. For those indicators, the highest influence was noted for delimbing operations (approx. 35%)., followed by harvesting (approx. 27%) and ground disking (approx. 17%).

The operations influence was similar for EP-f, WDP, and GWP-luluc. Power sawing (57.8%) and harvesting (42.2%) were the operations that had the highest influence. The EP-f, WDP, and GWP-luluc impacts were mainly influenced by phosphate emissions to the water, water extraction, and “carbon dioxide, land transformation”, respectively. The power sawing operation had the highest influence on the HTP-nc (40.9%) and HTP-c (76.5%) categories due to the emissions resulting from petrol combustion.

The delimbing (44.8%) and harvesting (31.3%) operations had the highest impacts on the ADP-f category due to the petroleum extraction and production. For the ADP-m category, the highest impacts were noted for harvesting (39.8%), delimbing (29.8%) and power sawing operations (22.9%) caused by zinc mining operations.

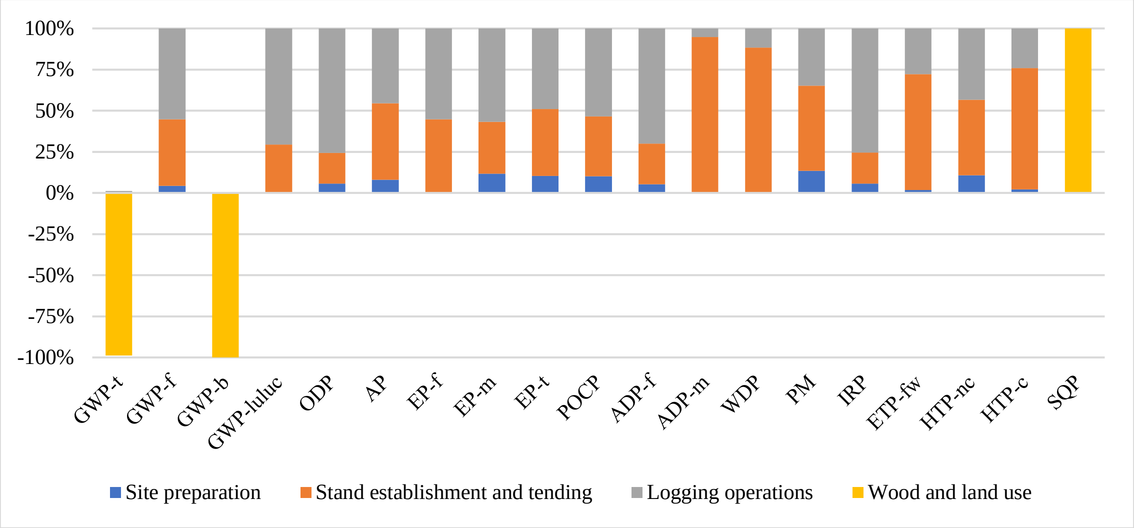

Figure 71 - Comparison of environmental impacts per forest management operation of Euc_Plant_PT scenario

For the Euc_Plant_MP scenario, shown in Figure 71, logging operations were the ones with the highest influence on GWP-f, GWP-luluc, ODP, EP-f, EP-m, EP-t, POCP, ADP-f and IRP categories. The stand establishment and tending operations showed a higher influence on the AP, ADP-m, WDP, IRP, ETP-fw, HTP-nc and HTP-c categories. Site preparation had the lowest influence on the environmental impacts of all categories.

For the GWP-f indicators, nitrogen fertilizer (32%) had the highest influence, followed by the harvesting (25.5%) and delimbing (25.5%) operations. Nitrogen acid production (used for nitrogen fertilizer production) and petrol combustion (during harvesting and delimbing operations) showed the highest influence on the GWP-f indicators.

Similarly to the results of the Crypt_Plant_MP scenario, the ODP and IRP indicators showed a high influence of logging operations because of the emissions of Halon 1301 to the air, resulting from petrol production. Delimbing (34.8%) and harvesting (34.7%) had the highest influence on both indicators.

For the EP categories, harvesting had the highest impacts on the EP-f (54.8%) and EP-m (27.2%) categories. Production of nitrogen fertilizer was the scenario that had the highest impact (61.9%) on the EP-t category, due to the blasting operations for resource extraction.

The use of nitrogen fertilizer for Eucalyptus production was the operation that showed the highest impacts on the ETP-fw (61.9%), WDP (66.1%), GWP-f (32%), PM (36.9%), and AP (31.4%) categories. Phosphate fertilizer had the highest impacts on the ADP-m category (75.6%) because of the zinc mining operations (74.7%). Power sawing was the operation that had the highest impact on HTP-c (35.6%) and HTP-nc (21.6%) categories, because of formaldehyde and carbon monoxide emissions to the air resulting from petrol combustion. For ADP-f, harvesting (32.3%) and delimbing (32.3%) had the highest influence.

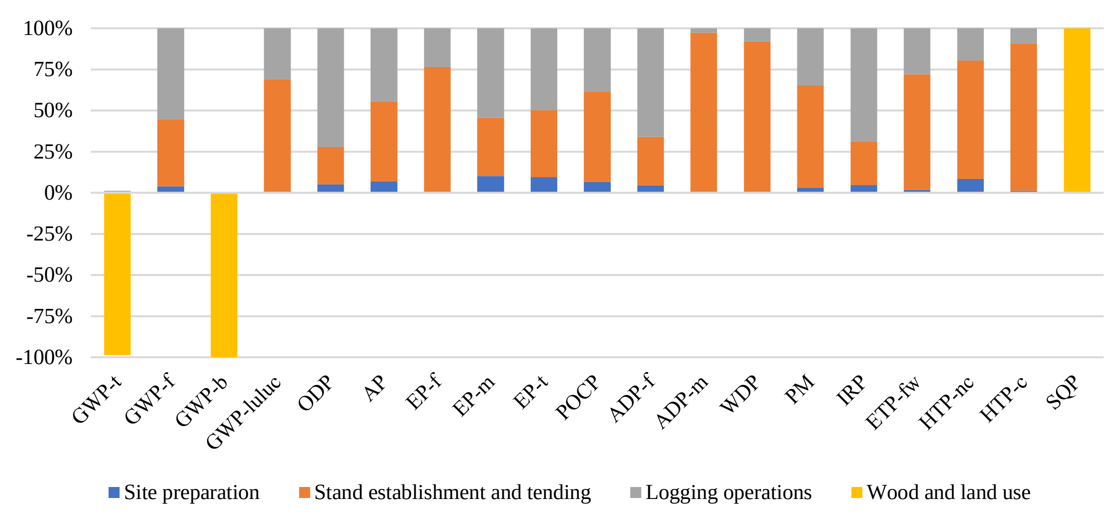

Figure 72 - Comparison of environmental impacts per forest management operation of MP_Plant_PT scenario

As seen in Figure 72, for the MP_Plant_PT scenario, the stand establishment and tending operations had the highest impacts on GWP-luluc, AP, EP-f, POCP, ADP-m, WDP, PM, ETP-fw, HTP.nc and HTP-c; and logging operations had the highest impacts on the GWP-f, ODP, EP-m, EP-t, ADP-f, and IRP categories. The delimbing and harvesting operations had the highest influence on logging operations.

GWP-f was mainly due to the carbon dioxide (80.1%) and dinitrogen monoxide (14.9%) emissions to the air, during the operations of delimbing (29.7%), nitrogen fertilising (24.0%), and harvesting (20.8%).

The power sawing operations had the highest influence on GWP-luluc (67.4%), HTP-c (64.0%), EP-f (50.7%), HTP-nc (44.3%), and POCP (35.7%). The emissions of formaldehyde and benzo(a)pyrene were the main responsible for HTP-c impacts, and carbon monoxide emissions were the main responsible for HTP-nc impacts. NVOC and carbon monoxide emissions to the air were the main responsible for POCP impacts.

Phosphate and nitrogen fertilising had the highest impact on PM, WDP, ETP-fw, and ADP-m categories. Phosphate fertilising represented the highest contribution to the ADP-m category (88.7%), due to the zinc mining operations for phosphate production. Nitrogen fertilising was the fertilizer used that had the highest contribution to the PM, WDP, and ETP-fw categories. The ETP-fw and WDP impacts of nitrogen fertilising (48.2% and 41.6%) were mainly due to the blasting and ammonia production operations, respectively. Production of nitric acid for nitrogen fertiliser (26.0%) and production of phosphate for phosphate fertiliser (27.7%) were the scenarios that had the highest effect on the PM category.

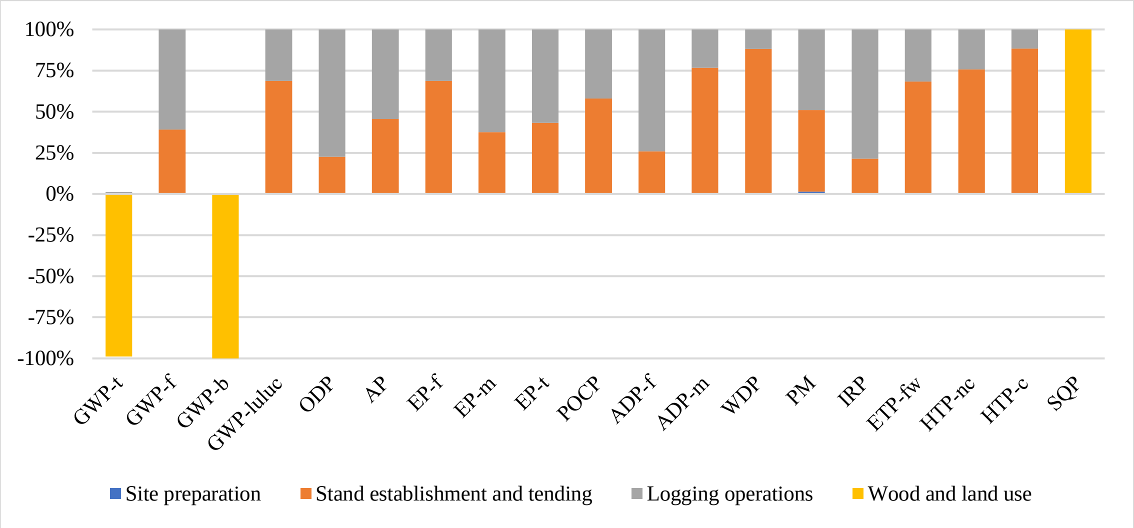

Figure 73 - Comparison of environmental impacts per forest management operation of MP_NR_PT scenario

As seen in Figure 73, for the MP_NR_PT scenario, it can be seen that the stand establishment and tending operations had the highest impacts on GWP-luluc, EP-f, POCP, ADP-m, WDP, PM, ETP-fw, HTP-nc, and HTP-c. The logging operations had the highest impacts on GWP-f, ODP, AP, EP-m, EP-t, ADP-f, and IRP. The influence of site preparation operations (road construction and maintenance) was less than 1.5% on all categories.

Carbon dioxide emissions to the air (78.7%) caused by delimbing operations (32.5%) represented the highest contribution to the GWP-t category. The ODP and IR categories were mainly due to the Halon 1301 (96.8%) and Carbon-14 (99.5%) emissions into the air, respectively. Delimbing operations contributed 42.0% and harvesting 29.0% to the ODP and IR impacts.

EP-m and EP-t were mainly due to the emissions of nitrogen oxides (92.9% and 70.0%, respectively) to the air. The diesel combustion was responsible for 25.2% and 23.5% of the emissions contributing to EP-m and EP-t, respectively. Delimbing was the operation that most contributed to the EP-m (31.3%) and EP-t (29.2%) categories.

The ADP-f category was mainly due to the petroleum extraction operations (84.3%). Delimbing was the operation that had the highest impact on ADP-f (39.7%), followed by harvesting (27.8%). Nitrogen fertilising was the operation that had the highest impact on the ADP-m category (64.4%), mainly due to the zinc mining operation (75.3%).

Power sawing was the operation that had the highest impacts on HTP-c (79.5%) and HTP-nc (54.7%) categories. Emissions of formaldehyde to the air were responsible for 74.6% of the HTP-c category, mainly from petrol combustion during power sawing operations. Carbon monoxide emissions to the air from petrol combustion during power sawing operations were responsible for 65.6 % of the HTP-nc category.

For the MP_Seed_PT scenario, stand establishment and tending operations had the highest impacts on the GWP-luluc, AP, EP-f, POCP, ADP-m, WDP, PM, ETP-fw, HTP-nc, and HTP-c categories. Logging operations had the highest impacts on the GWP-f, ODP, EP-m, EP-t, ADP-f, and IRP categories. Site preparation had the lowest impacts on all categories.

GWP-f was mainly due to the carbon dioxide (79.7%) emissions to the air. Delimbing, nitrogen fertilising and harvesting operations were the main contributors to this category with 30.3%, 24.5% and 21.2%, respectively. ODP and IRP had similar impacts and were mainly due to Halon 1301 (96.5%) and Carbon-14 (97.5%) emissions into the air, respectively. Delimbing (39.0%) and harvesting (27.0%) were the operations with the highest influence on those categories.

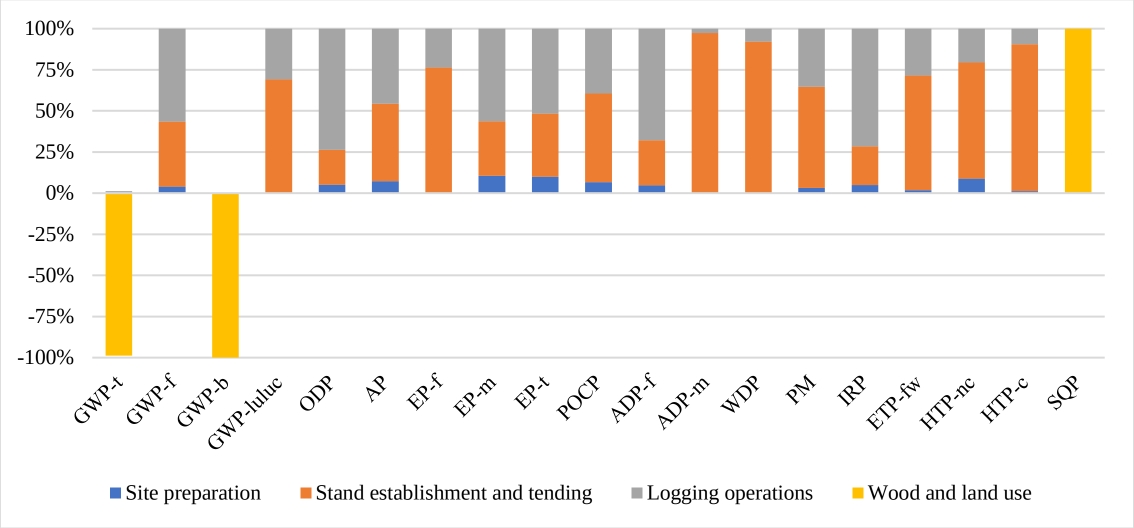

Figure 74 - Comparison of environmental impacts per forest management operation of MP_Seed_PT scenario

Phosphate emissions to the water represented the highest contribution (94.8%) to EP-f, mainly due to the power sawing (50.9%), phosphate fertilizer (24.3%) and harvesting (23.5%) operations. EP-m and EP-t were mainly due to the emissions of Nitrogen oxides (93.3% and 87.2%, respectively) to the air. Harvesting was the operation that had the highest influence on both categories (28.2% and 26.5%, respectively).

Phosphate fertilising was the operation responsible for 88.8% of ADP-m impacts, mainly due to the zinc mining operations (95.5%). Harvesting was the operation that had the highest influence on the ADP-f category (36.3%), mainly due to the petroleum extraction operations (80.5%).

Power sawing was the operation that had the highest impacts on the HTP-c (64.6%) and HTP-nc (46.3%) categories. Emissions of formaldehyde to the air were responsible for 60.6% of the HTP-c category and carbon monoxide emissions to the air from petrol combustion during power sawing operations were responsible for 55.9 % of the HTP-nc category.

8.1.3 Economic allocation

The modelling procedures made in Chapter 6 used a volumetric allocation of the outputs of the system boundary. Therefore, the percentages used for allocation were determined based on the ratio between the biomass volume produced and the roundwood volume produced. The amount of biomass and roundwood produced per ha per period considered and the volumetric percentage are shown in Table 65.

Table 65 - Biomass and roundwood produced per ha and volumetric percentage of products

Forest management scenario	**Volume produced**		**Allocation percentages**	
	Biomass	Sawnwood	Biomass	Sawnwood
Units	m^3/ha	m^3/ha	%	
MP_Seed_PT	92.0	412.8	18.2	81.8
MP_NR_PT	86.4	412.8	17.3	82.7
MP_Plant_PT	86.4	412.8	17.3	82.7
Euc_Plant_PT	46.5	697.5	6.3	93.8
Cryp_Plant_PT	128.7	429.0	23.1	76.9

In this section, an economic allocation of the roundwood production of Portuguese wood species is performed, the environmental impacts using an economic allocation are calculated, and these are compared with the environmental impacts using a volumetric allocation. The economic values of biomass and roundwood were determined based on mean market prices of 2016, given by a forest management company. The prices inventoried for biomass and roundwood were 20.00€ and 50.00€ per tonne, respectively.

To determine the percentage used for economic allocation, the total mass of each product produced per ha was multiplied by the price of products per tonnes. Then, to calculate the percentage used for economic allocation, the total revenue of a specific product was divided by the total revenue of the products obtained per hectare. For each product, the tonnes obtained per ha, economic values per ha and the economic percentages are shown in Table 66.

Table 66 – Calculation of economic allocation percentages

Forest management scenarios	**Mass produced per hectare**		**Total price per hectare**		**Allocation percentages**	
	Biomass	Roundwood	Biomass	Roundwood	Biomass	Roundwood
Units	Tones/ha	Tones/ha	€/ha	€/ha	%	%
MP_Seed_PT	55	246	1,098	12,322	8.2	91.8
MP_NR_PT	52	246	1,032	12,322	7.7	92.3
MP_Plant_PT	52	246	1,032	12,322	7.7	92.3
Euc_Plant_PT	42	631	842	31,572	2.6	97.4
Cryp_Plant_PT	40	133	795	6,628	10.7	89.3

The environmental impacts calculated per cubic meter of roundwood considering an economic allocation are shown in Table J-1 of Annex J. Since ETP-fw showed one of the highest values for normalised impacts, it was used to compare and discuss the allocation procedures studied. The comparison between various allocation procedures is shown in Figure 75.

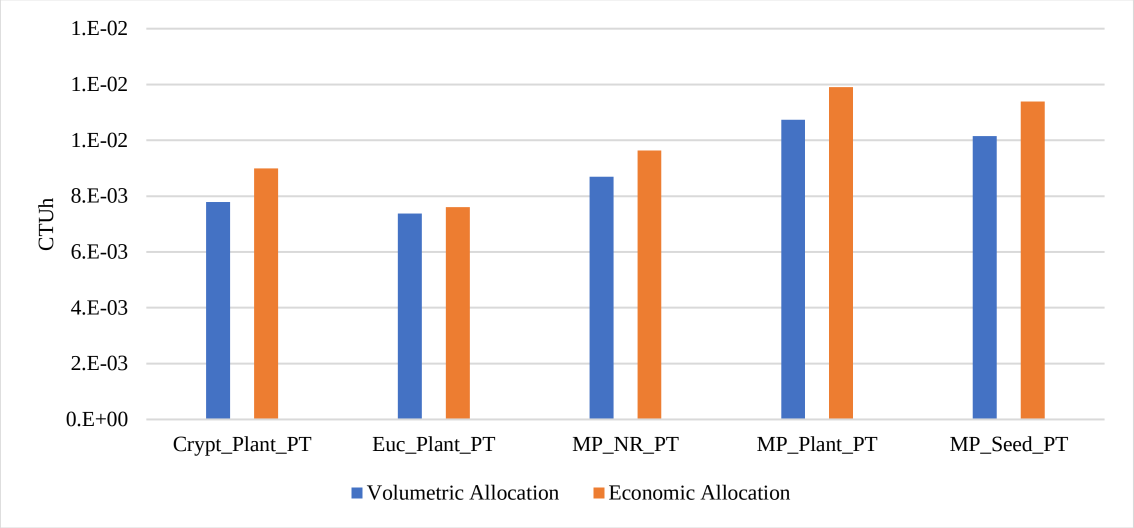

Figure 75 – Comparison of ETP-fw impacts of volumetric and economic allocation procedures for roundwood

Figure 75 shows that using an economic allocation increases the environmental impacts of roundwood. The lowest difference of impacts was noted for Euc_Plant_PT (3.2%) and the highest one for Crypt_Plant_MP (15.6%). As seen in Table 66, the use of an economic allocation increases the allocation percentage of roundwood and reduces the one of biomass.

As the price and volume of roundwood is higher than those of biomass, and the percentages used for economic allocation multiply the price and volume of products, using an economic allocation increases the difference between allocation percentages of various products. The increase in difference between allocation percentages of both products of the same modelling procedures leads to an increase in the environmental impacts of products with higher allocation percentage and decreases the environmental impacts of products with lower allocation percentage.

According to the EN 15804+A2, when the difference in revenue from the co-products is higher than 25%, the allocation procedure shall be based on economic values. Therefore, this study should follow an economic allocation. This type of attribution leads to the loss of the physical relationships of the materials and could compromise the conclusions of the subsequent LCA phases of this study. For this reason, a volumetric allocation was assumed. Thus, whenever the environmental impacts of roundwood and biomass are to be calculated, economic allocations should be followed.

8.1.4 Variations of LCI modelling procedures – National documents

The inventory of Portuguese forest management operations was performed based on the processes available in the Ecoinvent database (Wernet *et al.*, 2016). The LCI stage of LCA studies found in the literature review (Dias *et al.*, 2007; Dias & Arroja, 2012; Ferreira *et al.*, 2021) calculated the diesel, petrol and lubricant consumed during those machinery operations, based on the information provided by national databases (Monitoring Committee for Forestry Operations (CAOF), etc). In order to compare both LCI methodologies for forest machinery operations (based on the Ecoinvent database – "EDB methodology" and based on national databases – "NDB methodology"), this section compare their environmental impacts.

This section quantified the inputs and outputs resulting from the diesel, petrol and lubricant consumption of each forest management operations and these consumptions per hectare of forest management. Then, the environmental impacts of this LCI methodology were calculated and compared with the environmental impacts calculated in Section 7.3.1.

The inputs and outputs resulting from diesel production and consumption, petrol production and consumption and lubricant production were calculated based on "Diesel, burned in building machine {GLO}| processing", "Petrol, unleaded, burned in machinery {GLO}| petrol, unleaded, burned in machinery", and "Lubricating oil {RER}| market for lubricating oil" process from the Ecoinvent database (Wernet *et al.*, 2016), respectively.

The diesel, petrol and lubricant consumption was calculated based on the LCI data provided by Dias & Arroja (2012). The yield of operations and diesel and petrol consumption are shown in Table 67. The lubricant consumption was calculated based on Dias & Arroja (2012) calculation, which was given by 5% of the diesel (or petrol) consumption summed by the petrol consumption divided by 25 (mixing of petrol with oil). The total amount of diesel, petrol and lubricant are given in Table 68.

The environmental impacts were calculated and are shown in Table K-1 of Annex K. The environmental impacts of this modelling procedures were compared with the environmental impacts calculated in Section 7.3.1 and are shown normalised in Figure 76 and Figure 77 for core and additional impact categories, respectively.

For core categories, shown in Figure 76, the use of NDB had higher impacts for AP, EP-m, EP-t, POCP, and ADP-m. GWP-b impacts are similar for both LCI methodologies. The highest difference between both LCI methodologies was noted for the GWP-luluc category, where the environmental impacts of the NBD methodology were 0.1%, 0.3%, 1.7%, 1.8%, 1.9% of the EDB methodology, for Crypt_Plant_PT, MP_NR_Pt, MP_Seed_PT, MP_Plant_PT and Euc_Plant_PT, respectively. Excluding the GWP-luluc category, the highest difference between both LCI methodologies was noted for EP-f (mean of 67.7%), followed by EP-m (mean of 33.8%) and EP-t (mean of 32.5%).

Table 67 – Diesel and petrol consumption and yield of forest management operations

Forest operations		Fuel type	hr/ha	hr/m3	l/hr
Site preparation	Harrowing with disk harrow	Diesel	3.5	-	13.5
	Ploughing	Diesel	4.3	-	20.5
	Subsoiling with subsoiler plow	Diesel	3.0	-	14.5
	Road construction	Diesel	0.6	-	15.0
	Road maintenance	Diesel	0.6	-	14.0
Stand establishment and tending	Mechanical weed control with forwarder	Diesel	1.3	-	11.5
	Thinning and pruning with power saw	Petrol	9.0	-	1.00
	Forwarding of thinned logs with forwarder	Diesel	-	0.02	12.0
Logging operations	Final harvesting with harvester	Diesel	-	0.10	12.0
	Extraction with tractor	Diesel	-	0.08	12.0
	Forwarding with forwarder	Diesel	-	0.02	12.0

Table 68 – Total diesel, petrol and lubricant consumption of each forest management scenario

Forest management scenario	Diesel	Petrol	Lubricant
Units	MJ	MJ	kg
MP_Seed_PT	97.11	3.069	0.117
MP_NR_PT	88.03	3.069	0.107
MP_Plant_PT	98.29	3.069	0.119
Euc_Plant_PT	116.98	0.908	0.135
Cryp_Plant_PT	106.60	2.215	0.126

The environmental impacts of EDB scenarios for GWP-luluc were mainly due to the “carbon dioxide, land transformation” emissions during harvesting and power sawing operations. For NDB, this category is mainly due to the “carbon dioxide, land transformation” emissions from phosphate fertilising operations.

The EP-f impact of scenarios that used the EDB methodology was mainly due to the phosphate emissions during harvesting, power sawing and phosphate fertilising operations. For the NDB scenarios, this category was mainly due to the phosphate fertilising operations. A further analysis showed that the processes used to model the EDB scenarios considered the use of vegetable oil for lubricating chain saws, which increased phosphate emissions. The harvesting and power sawing operations of NDB scenarios did not consider the use of lubricating oil instead of vegetable oil.

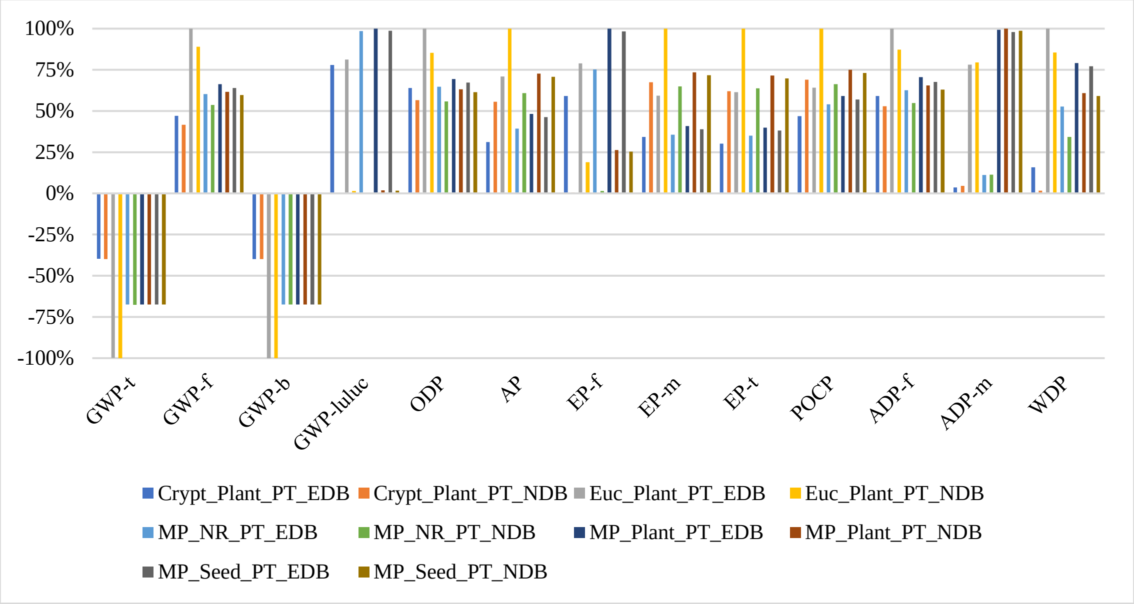

Figure 76 – Relative core environmental impacts of forest management operation based on the Ecoinvent database (EDB) and national databases (NDB)

The EP-m and EP-t categories of EDB scenarios were mainly due to the nitrogen oxides, during harvesting, delimbing, nitrogen fertilising, and ploughing. For NDB scenarios and EP-m and EP-t categories, the impact values were mainly due to the nitrogen emissions from diesel combustion. A further analysis identified that the emissions resulting from diesel combustion from processes operations (such as “Delimbing/sorting, excavator-based processor {RER}”) and from diesel combustion followed different methodologies for the calculation of emissions.

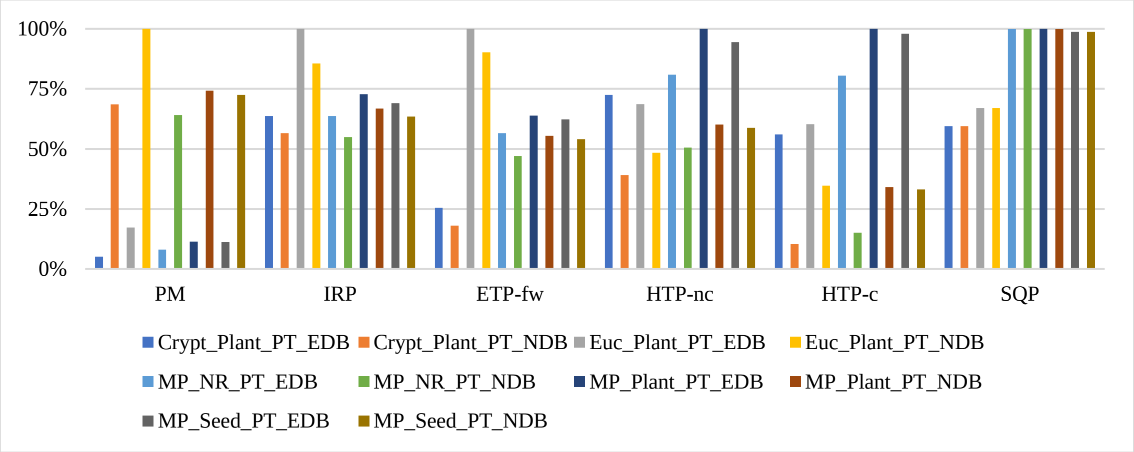

Figure 77 - Relative core environmental impacts of forest management operation based on the Ecoinvent database (EDB) and national databases (NDB)

For additional impact categories, shown in Figure 77, EDB has higher impacts on IRP, ETP-fw, HTP-nc, and HTP-c categories. For the SQP category, the NBD and EDB methodologies showed similar impact values. The highest difference of impact between NBD and EDB methodologies was noted for PM (mean of 65.3%), HTP-c (mean of 53.5%) and HTP-nc (mean of 31.9%) categories.

For NDB, PM was mainly due to the emissions of "Particulates, <2.5 um" resulting from diesel combustion. For EDB, the impacts of this category were mainly due to the production of diesel and phosphate. A further analysis identified that the diesel combustion assumed for EDB did not consider the same methodology for "Particulates, <2.5 um" emissions quantification.

For NDB and EDB, HTP-nc was mainly due to the carbon monoxide emissions to the air resulting from petrol combustion. For EDB and NBD, HTP-c was mainly due to the formaldehyde and chromium emissions to the air resulting from petrol combustion, respectively. A further analysis identified that the quantification of emissions for EDB and NDB followed different methodologies, which influenced the impact values.

8.2 **Structural products**

8.2.1 Comparison of results with ReVa results

This section intends to compare the environmental impacts of SW, GLT and LVL products described in Section 5 with the ReVa of environmental impacts calculated in Section 2.5 by Native LCA methodology (Silvestre et al., 2015). As the ReVa was calculated by the "CML 2001 v 2.05 and West Europe – 1995" methodology, the LCIA for the products assessed in this study followed here the same methodology. The results are shown in Table L-1 of Annex L, and presented normalised in Figure 78, Figure 79, and Figure 80 for SW, GLT and LVL, respectively.

Figure 78 shows that SW_ReVa had the highest impacts on the ODP category. For the other categories, Eucalyptus had the highest impacts on AP and EP; Maritime pine had the highest impacts on POCP, ADPE and ODP; and Cryptomeria had the highest impacts on GWP. Cryptomeria had the lowest impacts on all categories, except GWP, where Eucalyptus had the lowest impacts.

The environmental impacts of the various scenarios modelled in this study were inside the standard deviation range of the EPD_SW_ReVa scenario, except for the Maritime pine environmental impacts on POCP and the Maritime pine, Eucalyptus and

Cryptomeria scenarios on the GWP category. A further analysis identified that the high impacts on POCP were related to the diesel and petrol production and combustion during the forest management operations. The impacts of GWP were mainly related to the biogenic carbon retained in wood-based products, and, as shown before, the biogenic carbon retained is related to the density of products. As the Maritime pine and Eucalyptus have higher density than Swedish and German's products and than products studied in EPD_SW_ReVa, then GWP impacts were lower for the Maritime pine and Eucalyptus solutions for each m^3.

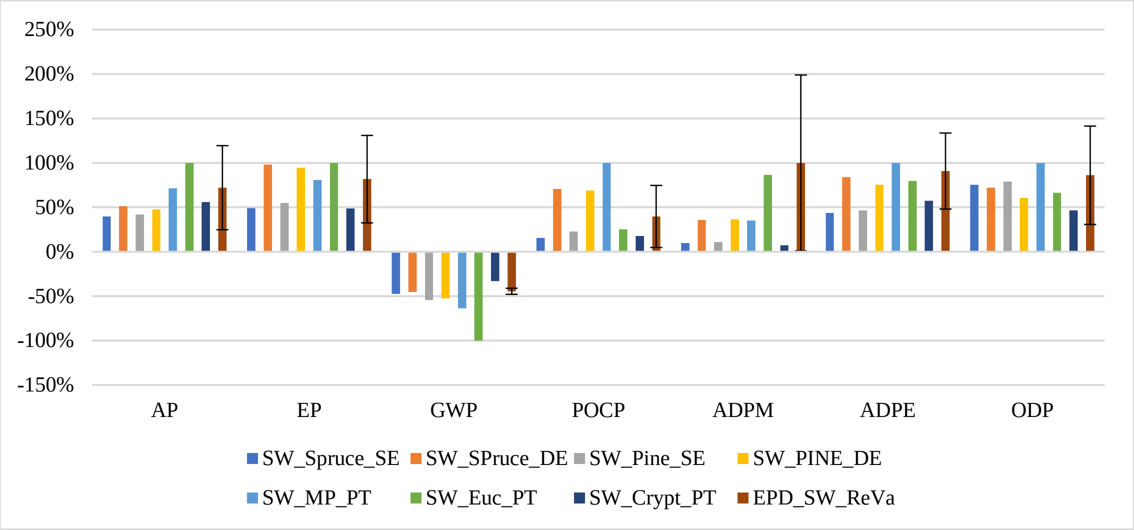

Figure 78 – Comparison of environmental impacts of SW scenarios with EPD_SW_ReVa

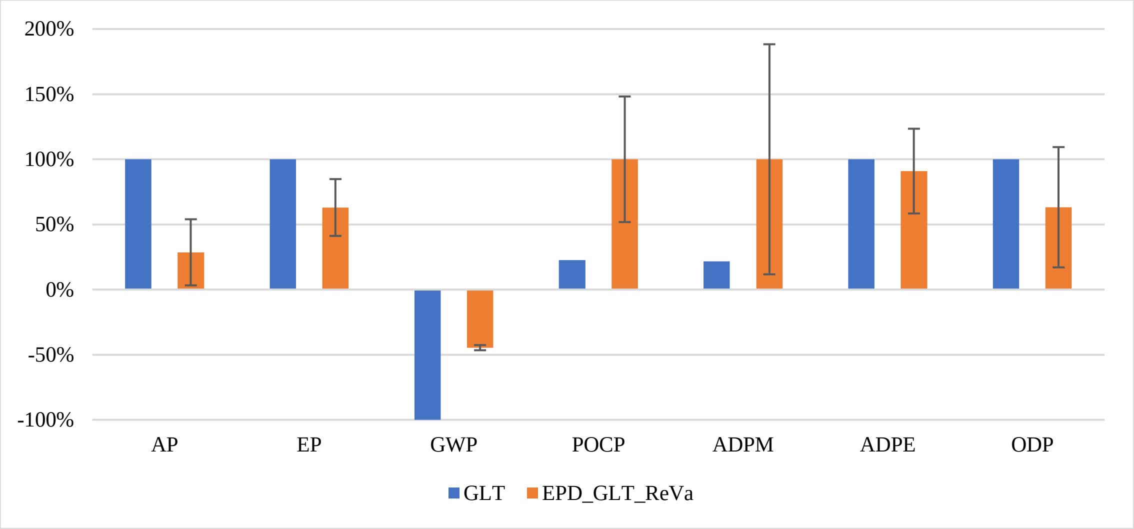

Figure 79 – Comparison of the environmental impacts of GLT scenario with EPD_GLT_ReVa

For glulam products, shown in Figure 79, the EPD_GLT_ReVa scenario had the lowest impacts on the AP, EP, ADPE and ODP categories. The highest difference between GLT impacts and EPD_GLT_ReVa was noted for ADPM (78.5 %), followed by POCP (77.3 %) and AP (71.4%). GWP was the category that showed the highest difference between the standard deviation range values of EPD_GLT_ReVa and GLT.

As noted in Section 2.5, the calculation of the GWP category was highly influenced by the biogenic carbon sequestered during stage A1. The GWP impacts of GLT and EPD_GLT_ReVa were -1,445.14 kg CO_2 eq. and -644.45 kg CO_2 eq. respectively. The main influence on the GWP category of the GLT scenario was due to the sawnwood production operations. A further analysis showed that the difference between both scenarios was mainly due to the methodology used to consider the biogenic carbon dioxide of sawnwood products.

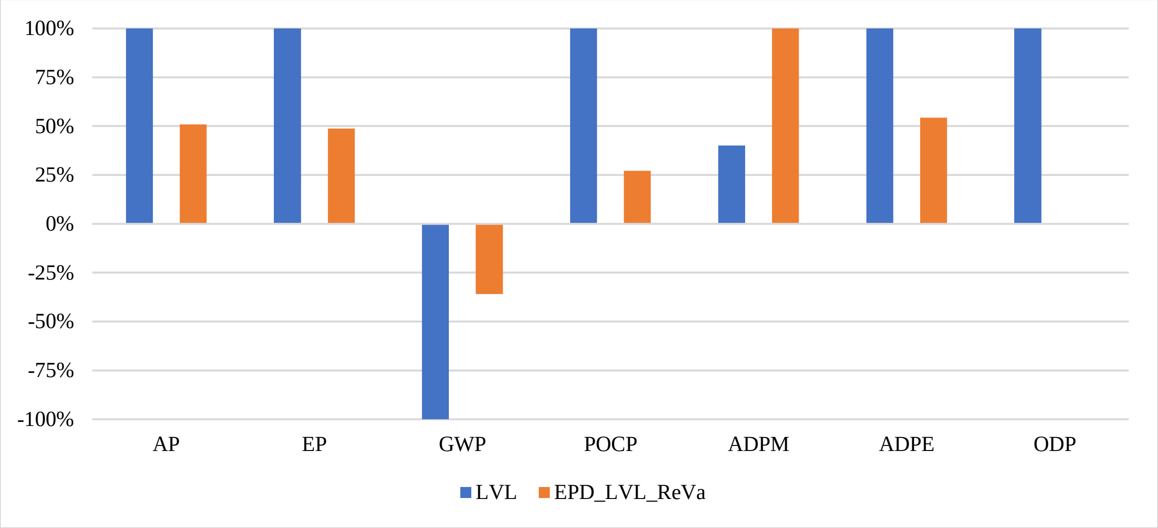

Figure 80– Comparison of the environmental impacts of LVL scenario with EPD_LVL_ReVa

Figure 80 shows that the LVL scenario had higher impact than the EPD_LVL_ReVa scenario on the AP, EP, POCP, ADPE and ODP categories. The highest difference between both scenarios was noted for ODP (99.9 %), followed by POCP (72.9 %) and GWP (64.1%).

A further analysis showed that the main influence on the ODP category of a LVL scenario was the pipeline transportation of natural gas (99.2%) used in urea production and urea formaldehyde (UF) adhesive production. According to the data available on the Ecoivent database (Wernet *et al.*, 2016), the LVL scenario assumed that the amount of adhesive was approximately 12.5% of the total weight of LVL. For the EPD_LVL_Reva scenario, the adhesive (phenol formaldehyde - PF) was 2.5% of the total mass of product. Those results showed that the adhesive amount and type influenced the ODP category results.

Similarly to the GWP impacts for glulam and sawnwood, the LVL impacts were higher for the EPDs used for ReVa calculation (-655.0 kg CO_2 eq.) than for the scenario modelled in this study (-1,824.5 kg CO_2 eq.). This was a consequence of the methodology used to consider the biogenic carbon dioxide of sawnwood products.

8.2.2 Changing the type of allocation for Maritime pine

The LCI performed in Section 6 of this study considered a volumetric allocation for the sawnwood production scenarios. The comparison of sawnwood results made in Section 7.3.2 found that the scenarios that were modelled by inquires to the production companies had lower impacts than those that were modelled by the Ecoinvent database processes. In this section, different allocation procedures for the production of Maritime pine sawnwood were considered, and the corresponding environmental impacts were calculated and compared for various allocation scenarios. The allocation scenarios for the modelling procedures of sawnwood production outputs (sawnwood, wood chips, sawdust, and bark) were volume, massic, economic and none allocation procedure (100% of output was sawnwood).

The relation between outputs of each allocation procedure is shown in Table 69. For volumetric allocation (performed in Section 6), the percentages were calculated based on the volume of each co-product resulting from sawnwood production. The volumetric percentage was calculated by dividing the volume of each product by the sum of all the volumes. The massic allocation percentages were established by determining the mass of each co-product and dividing each value by the total mass (sum of products mass). The density of each product was determined based on the values given by Viana *et al.* (2018). Economic allocation percentages were determined by considering the total revenue of each product (multiplying the volume by price per cubic meter) and dividing that value per the total revenue of the products (sum of products' revenues). The prices were determined by company inquiries in the year 2016. Additionally, only the scenario for the production of Maritime pine sawnwood was considered. The allocation percentages and the data used for their calculation are shown in Table 69.

The environmental impacts of each allocation procedure are shown in Tables M-1, M-2 and M-3 of Annex M, for volume, mass and economic allocations, respectively. As ETP-fw was one of the categories that showed higher normalised impacts, the corresponding environmental impacts of each allocation scenario were determined and compared in Figure 81.

Table 69 – Volume, mass and economic relations between products and allocation percentages

Products	Volume allocation		Mass allocation			Price allocation		
	Relation	Allocation	Density	Relation	Allocation	Price per m^3	Relation	Allocation
	m^3	%	kg/m^3	kg	%	€	€	%
Sawnwood	1.00	18.1	580	1.00	31.4	165.00	1.00	70.7
Wood chips	1.69	30.5	380	1.11	34.8	16.25	0.17	11.8
Sawdust	2.07	37.3	210	0.75	23.6	14.25	0.18	12.6
Bark	0.78	14.1	240	0.32	10.2	14.75	0.07	5.0

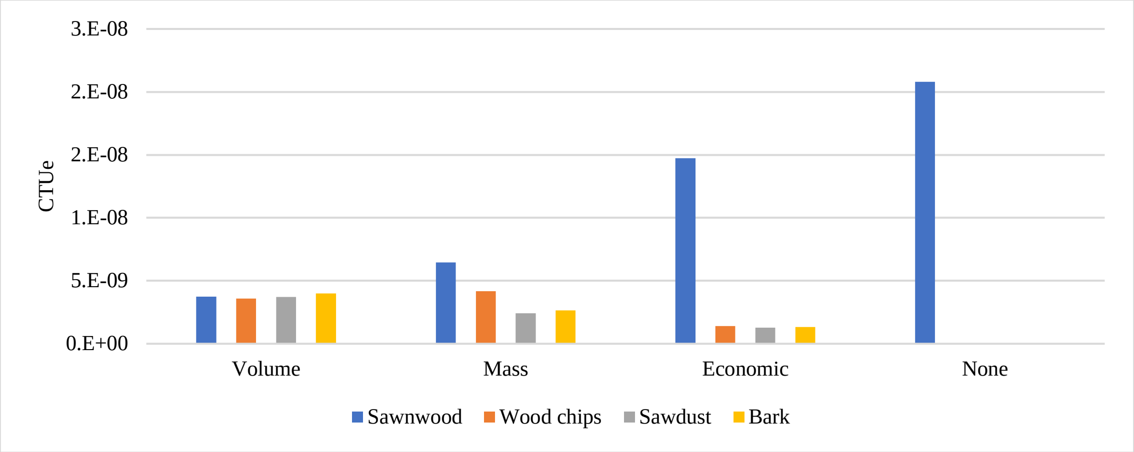

Figure 81 – Comparison of ETP-fw impacts of volume, mass, economic and “none” allocation procedures

For ETP-fw, shown in Figure 81, the allocation procedure that showed the highest values for sawnwood was the one that did not consider co-product production, followed by economic and mass procedures. The environmental impacts of Maritime pine sawnwood for volume, mass and economic allocation procedures were 18%, 31% and 71% of the impacts of the procedure that did not consider any co-products production, respectively.

For each allocation procedure, Maritime pine sawnwood was the product that had the highest environmental impacts, except on volume allocation, where bark had the highest impacts, followed by sawnwood (94% of bark), sawdust (93% of bark) and wood chips (90% of bark). For the massic allocation procedure, the highest contribution was noted by sawnwood, followed by wood chips (65% of sawnwood), bark (41% of sawnwood) and sawdust (37% of sawnwood). For the economic allocation procedure, the highest contribution was also noted by sawnwood, followed by wood chips (10% of sawnwood), bark (9% of sawnwood) and sawdust (8% of sawnwood).

The economic allocation procedure was the scenario that had the lowest impacts on wood chips, sawdust and bark. The environmental impacts of the volumetric allocation procedure showed similar values for the various products studied (the highest difference was between bark and sawdust – 7%).

8.2.3 Life cycle impacts of Maritime pine SW production operations

One of the main objectives of this chapter is to identify environmental “hotspots” of the Maritime pine sawnwood production. This section calculated the influence of each process on the environmental categories of maritime sawnwood. The percentages of each operation in core and additional impact categories are shown in Figure 82 and in Figure 83, respectively. As the main objective is to make an analysis of the internal operations of the sawmill, the roundwood operations were excluded from this assessment.

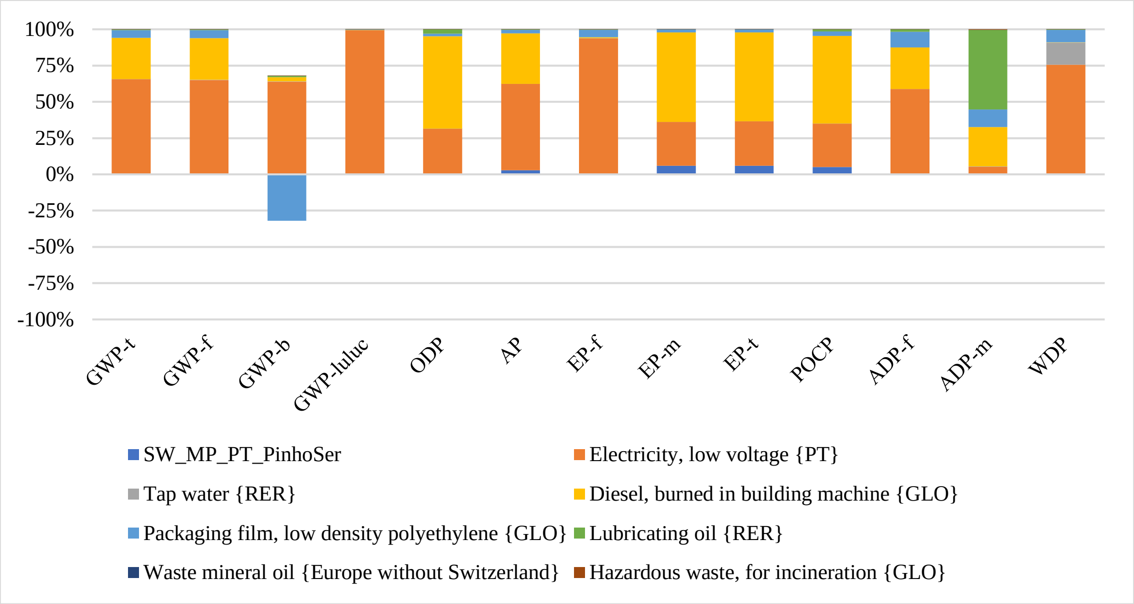

Figure 82 - Comparison of core environmental impacts per sawnwood management operation of SW_MP_PT scenario

For the core environmental impacts of sawnwood production stage (A3), shown in Figure 82, the electricity consumption had the highest impacts on GWP-t (65.4%), GWP-f (65.0%), GWP-b (63.9%), GWP-luluc (99.5%), AP (59.4%), EP-f (93.8%), ADP-f (58.8%) and WDP (75.6%). Diesel production and combustion had the highest impacts on the ODP (63.7%), EP-m (61.7%), EP-t (61.2%), and POCP (60.3%) categories. Lubricant oil consumption had the highest impacts on the ADP-m (54.9%) category. Packaging film had negative impacts on the GWP-f category (32.0%) due to the carbon positive effects of sawnwood used for pallets production and used on plastic film extrusion operations.

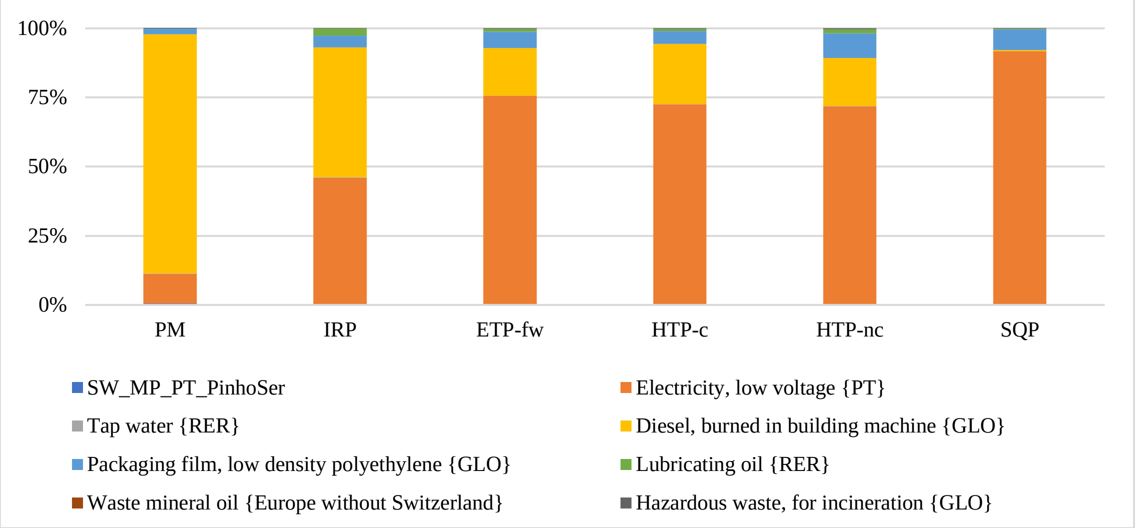

Figure 83 - Comparison of additional environmental impacts per sawnwood management operation of SW_MP_PT scenario

According to Figure 83, for additional environmental categories, the electricity consumption had the highest impact on ETP-fw (75.6%), HTP-c (72.6%), HTP-nc (71.9%) and SQP (91.7%) categories. Diesel production and consumption had the highest impacts on the PM (86.5%) and IRP (47.0%) categories.

8.2.4 Comparison of environmental impacts of structural products taking into account the strength classes

The comparison performed in Section 7.3.2 for the environmental impacts of structural products did not take into account their structural performance. This section intends to compare the ETP-fw impacts of structural products using the mechanical grading methodology described in Section 4.2.2 and the bending and modulus of elasticity equivalent units described in section 4.3.

8.2.4.1 **Mechanical grading allocation**

The mechanical grading allocation procedures calculated in Section 4 were used in this section to compare the ETP-fw impacts of various strength classes of Maritime pine sawnwood. The yield used for the allocation of environmental impacts to strength classes was given in Table 25. The ETP-fw impacts of various strength classes are compared in Figure 84.

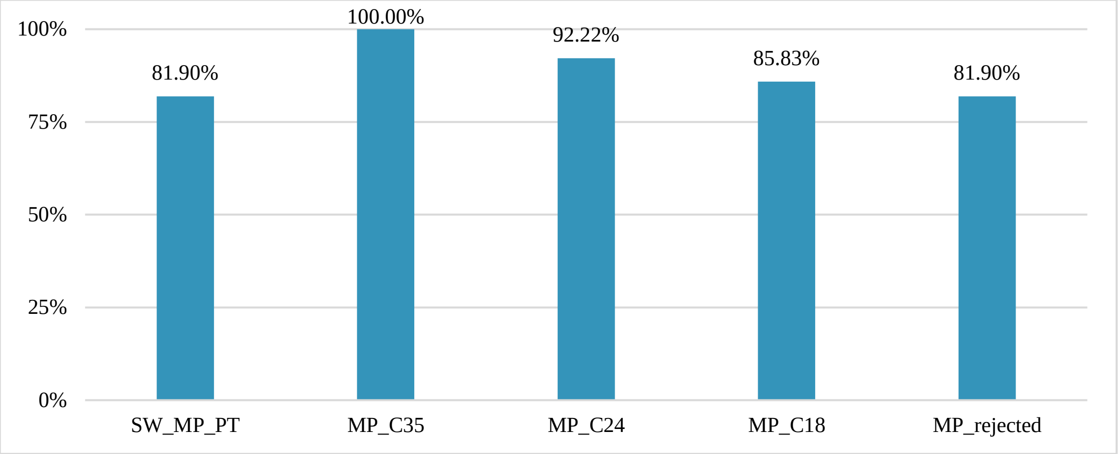

Figure 84 – Relative ETP-fw impacts of various strength classes of Maritime pine sawnwood

The results presented in Figure 84 show that the strength class with the highest impacts was C35, followed by C24, C18 and rejected wood. Rejected wood had similar impacts to those of Maritime pine bundle. The relation between the relative impacts of strength classes was similar to the relation between allocation yields (shown in Table 25).

From this analysis, it can be concluded that the environmental impacts were higher for the highest strength class and lower for the lowest ones.

8.2.4.2 **Bending strength and modulus of elasticity units**

As stated before, the comparison of the environmental impacts of structural products shall be performed taking into account the structural properties of products. This section compares the environmental impacts of various sawnwood structural products by taking into account the bending strength and modulus of elasticity properties. This comparison was made using the bending strength and modulus of elasticity units given in Section 4.3.

The environmental impacts of various scenarios are shown in Table O-1 and O-2 of Annex O for bending strength unit and modulus of elasticity unit, respectively. To simplify the analysis, the environmental impacts were compared by calculating the relative impacts of various scenarios on the ETP-fw category, which are shown in Figure 85.

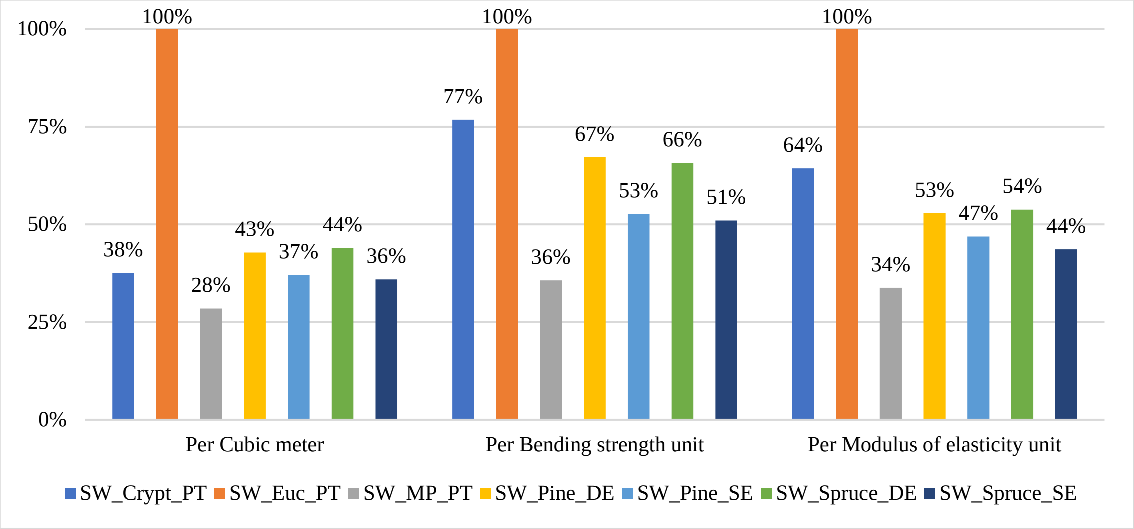

Figure 85 – Relative ETP-fw impacts of bending strength and modulus of elasticity units

For various units of comparison, Eucalyptus was the sawnwood scenario that had the highest impacts on ETP-fw. Maritime pine was the sawnwood scenario that had the lowest impacts on all categories. All the scenarios increased the relative impacts from the comparison per cubic meter to the comparison per bending strength and modulus of elasticity units.

The difference of impacts between the Eucalyptus scenario and all the other scenarios was higher when comparing impacts per cubic meter. As seen in Figure 85, this occurs because the Eucalyptus scenario was the scenario that required the lowest amount of volume for bending strength and modulus of elasticity functional units calculated in Section 4.3. The Cryptomeria scenario was the one that showed the highest increase of impacts from comparison of bending strength to modulus of elasticity units per cubic meter. This is because Cryptomeria was the one that requires the highest amount of volume for bending strength and modulus of elasticity functional units.

The analysis of these results showed that the consideration of bending strength and modulus of elasticity increased the relative impacts of products with lower properties. Comparing the bending strength and modulus of elasticity functional units, the relative impacts of bending strength units were higher for all scenarios than for modulus of elasticity units (in comparison with the Eucalyptus scenario).

8.3 **Structural floor solutions**

8.3.1 Design variables

8.3.1.1 **Pre-sizing**

The pre-sizing made in Section 4.4.2 assumed that the height of the beams was equal to the span divided by 20. According to Swedish Wood (2016b), there are other pre-sizing rules that can be followed (for example, assuming a ratio between the width and the height of beams). In this section, the volume of various structural solutions was compared assuming different pre-sizing rules. Three rules were compared: height of the beams equal to three times the width (h=3*w), height of the beams equal to two times the width (h=2*w), and height of beams equal to span divided by 20 (h=l/20) (rule adopted in this study). The pre-sizing of the IJ was made assuming that the width dimension is the width of the flanges, and the height dimension is the total height of the elements. The design procedure of the structural solutions was the one described in Section 4.4, ensuring the equivalence between all the solutions. The volumes of the solutions are shown in Figure 86.

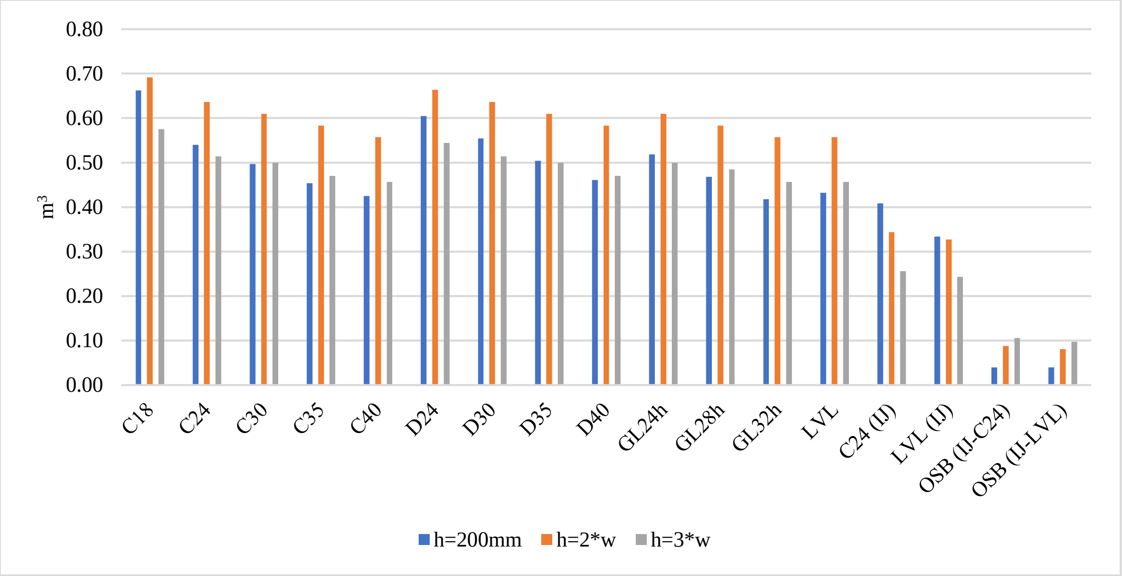

Figure 86 – Volume of various structural solutions from different pre-sizing rules

Figure 86 shows that the pre-sizing rule that required the highest volume on various scenarios was h=2*w, except for I-joists products (C24, LVL and OSB). For LVL and C24 products, the h=200 mm pre-sizing rule (used in this study) had the highest volume; and for OSB, the h=3*w had the highest volume. The h=3*w scenario had the lowest volume for the C18, C24, D24, D30, D35, and GL24h products. The “h=200mm” scenario had the lowest volume for C30, C35, C40, D40, GL28h, GL32h and LVL.

For rectangular cross-sections, the results showed that the pre-sizing rule h=2*w led to a higher volume than the other pre-sizing rules. Comparing the other pre-sizing results, for each product, the h=3*w volumes tended to be lower on scenarios of low strength classes and the h=200 mm volumes on scenarios of high strength classes.

8.3.1.2 **Middle span supported**

According to the Swedish Wood (2016b), the use of beams in perpendicular direction supporting the loads above them can increase the load capacity of floors. This section intends to compare the volume of the scenario studied before with a scenario that considers a middle span beam that supports the loads of the beams and of the floor system above them. The design procedure of the structural solutions was described in Section 4.4, ensuring the equivalence between all the solutions. The volumes are compared in Figure 87.

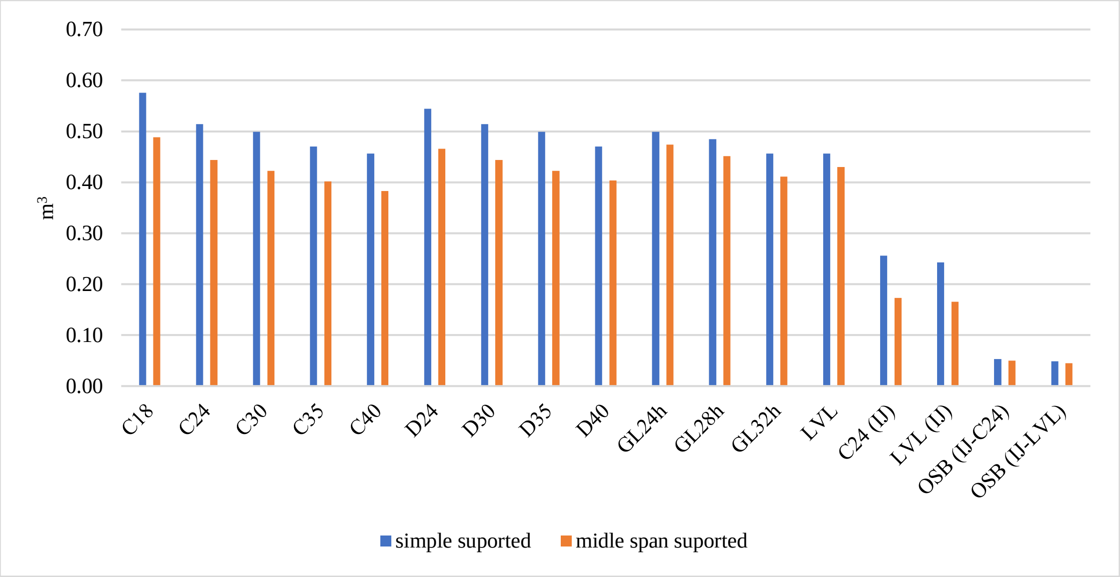

Figure 87 - Volume of various structural solutions with different architectural configurations

Figure 87 shows that the middle span supported scenario required lower volume than the simple supported scenario (considered before in this study). The difference between both scenarios was higher for I-Joists (flange products), followed by softwoods and hardwoods. The lower difference was noted for LVL, followed by GLT.

8.3.2 Modelling procedures of incineration with energy recovery

The literature review performed in this study found that one of the main advantages of wood products is the possibility of heat and/or energy production at their end-of-life. The energy and/or heat produced depends on the calorific value of wooden products. This section calculates and compares the full life cycle environmental impacts of various structural scenarios by considering the production of energy at their end-of-life. The amount of energy produced depends on the calorific value of each product, which were identified by literature review and are shown in Table 70.

Table 70 – Calculation of calorific values of various structural products per building solution

Building solution	**Density**	**Calorific values per products**		**Volume**	**Calorific values per solution**
Units	kg/m^3	MJ/kg	MJ/m^3	m^3	MJ
SW_MP_PT	597	20.43	12,196.7	0.497	6,061.8
SW_Euc_PT	905.3	19.62	17,761.9	0.460	8,184.7
SW_SPine_SE	490	19.52	9,564.8	0.540	5,165.0
SW_SPrc_SE	430	19.29	8,294.7	0.540	4,479.1
SW_SPine_DE	490	19.52	9,564.8	0.540	5,165.0
SW_SPrc_DE	430	19.29	8,294.7	0.540	4,479.1
GL_EU	420	19.00	7,980.0	0.518	4,136.8
LVL_EU	510	20.90	10,659.0	0.432	4,604.7
IJ_C24	431.5	16.00	6,904.0	0.408	2,818.5
IJ_LVL	514.2	16.00	8,227.8	0.333	2,745.8
OSB_ EU	550	17.30	9,515.0	0.400	3,806.0

The energy production at the end-of-life represents an output of energy from the system boundaries. According to the EN 15804+A2, these operations shall be taken into account in module D of the system boundary. In this study, the energy recovery was modelled by an output of energy from the system boundary equals to the calorific value of each product. This output was modelled by "Heat, district or industrial, other than natural gas {PT}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014" process of the Ecoinvent database (Wernet *et al.*, 2016). The environmental impacts of full life cycle (with energy recovery) are given in Table P-1 of Annex P and are compared in Figure 88 and in Figure 89.

Figure 88 shows that LVL had the highest impacts on all categories, except on GWP-b ADP-m, and WDP, where I-Joists made with LVL had the highest impacts. Maritime pine sawnwood had the lowest impacts on the GWP-t, GWP-f, GWP-luluc, EP-m, and ADP-f categories. Eucalyptus had the lowest impacts on the GWP-b, ODP, AP, EP-t and POCP categories. For the WDP and ADP-m categories, Spruce from Sweden had the lowest impacts.

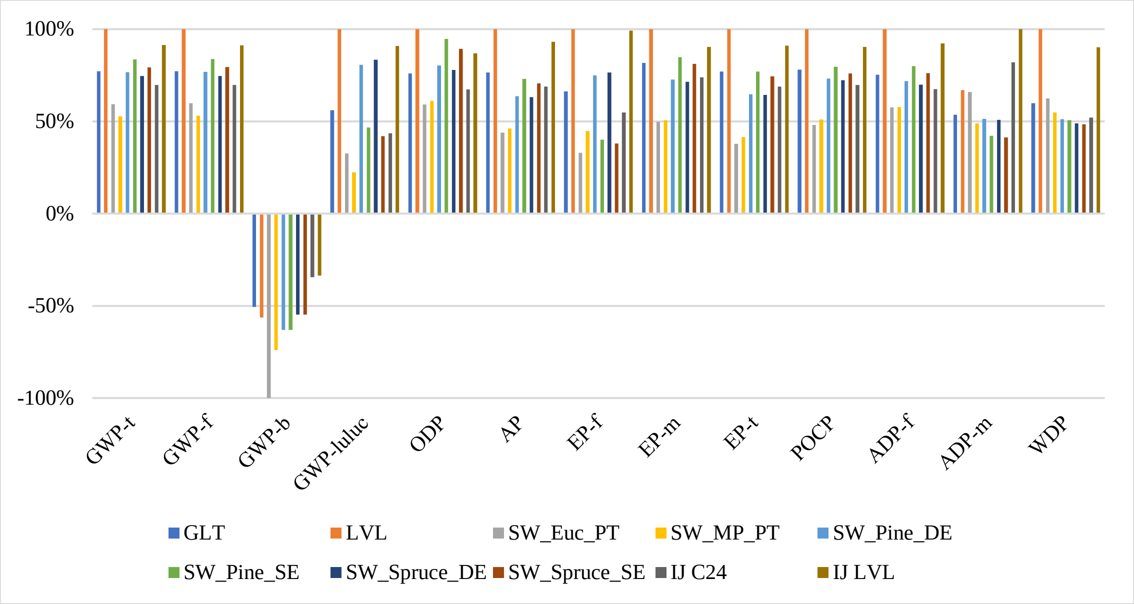

Figure 88 - Relative core environmental impacts of life cycle of building solutions with incineration and energy recovery of products

The main difference between the relative impacts of the LCA scenario that considers the energy recovery at the end-of-life and the scenario that does not was the GWP-b impacts. GWP-b had negative impacts because the impacts of energy production were subtracted from the life cycle impacts of various structural scenarios, which were zero for the GWP-b category.

Analysing the GWP-b impacts, this value should be equal to 0 since biogenic carbon captured during tree growth is emitted to the atmosphere during incineration of wood chips. This is not the case because the process used to model incineration does not consider the emission of biogenic carbon present in wood chips when burnt. In order to avoid this, biogenic carbon emissions should be modelled neutral.

For additional categories, LVL has the highest impacts on PM, IRP and HTP-nc; I-Joists made with LVL have the highest impacts on ETP-fw and HTP-c, and GLT had the highest impacts on SQP. Eucalyptus had the lowest impacts on the ETP-fw, HTp-c, HTP-nc and SQP categories, and Maritime pine had the lowest impacts on the PM and IRP categories.

The main difference between scenarios that consider incineration and incineration with energy production was in the ETP-fw category. For this category, Eucalyptus had negative impacts. It means that the benefits of the energy production were higher than the loads of the Eucalyptus sawnwood life cycle for the ETP-fw category.

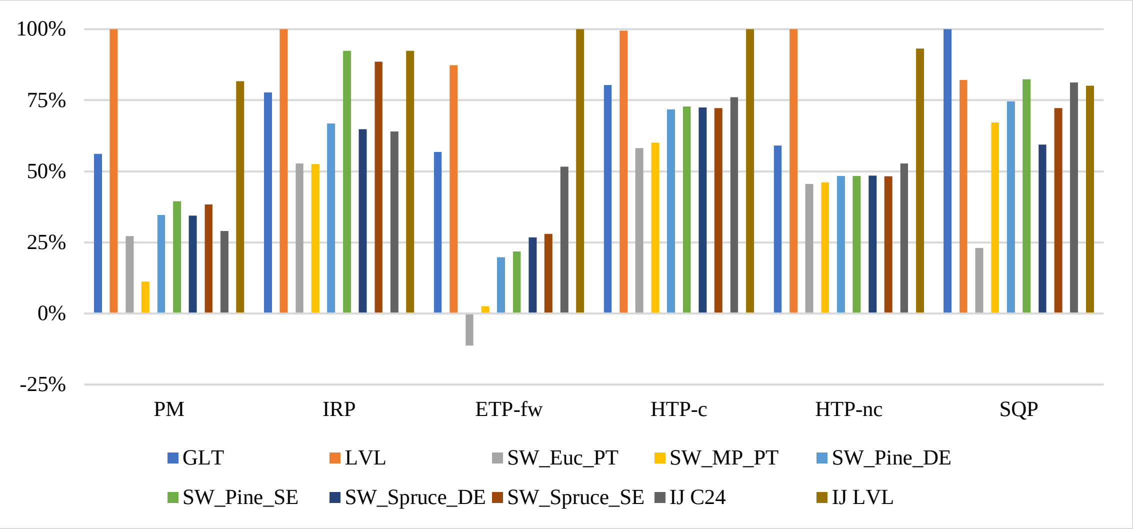

Figure 89 - Relative additional environmental impacts of life cycle of building solutions with incineration and energy recovery of products

A further analysis identified that the scenario with energy recovery at the end-of-life led to lower impacts than the scenario that did not consider energy recovery. The highest benefits were noted on the ETP-fw category (mean benefits of 398%) and for the Eucalyptus and Maritime pine sawnwood scenarios. The second highest benefits were noted on in the EP-t category (mean benefits of 136%), followed by SQP (mean benefits of 133%). The lowest benefits were noted for WDP (mean benefits of 101%), followed by ADP-f (mean benefits of 103%) and IRP (mean benefits of 103%). For the majority of the categories, the highest benefits were noted for the Eucalyptus scenario (mean benefits of 137%), followed by the Maritime pine scenario (mean benefits of 126%). The lowest benefits were noted for IJ made with LVL (mean benefits of 105%), followed by IJ made with C24 and LVL (both with mean benefits of 108%).

8.4 **Durability solutions**

8.4.1 Life cycle impacts per operations

The environmental impacts of various treatment scenarios vary per treatment type and wood specie. This section quantified the influence of wood products production, preservative treatment production, application of preservative treatments, use and end-of-life operations on the environmental impacts of Maritime pine treated scenarios. The core and additional environmental impacts of Maritime pine sawnwood with pressurised treatments are shown in Figure 90 and in Figure 91, respectively.

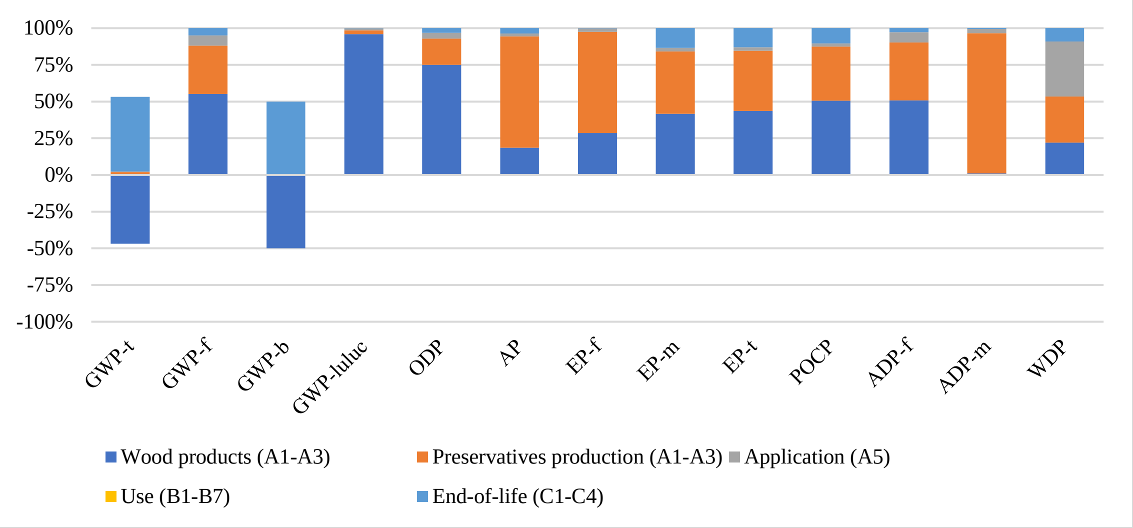

Figure 90 - Comparison of core environmental impacts of life cycle operations of MP_PT scenario

Figure 90 shows that the wood and preservatives production had the highest impacts for the majority of the impact categories. Wood production had the highest impacts on GWP-luluc (96.0%), ODP (75.0%), GWP-f (55.3%), ADP-f (50.9%), POCP (50.7%) and EP-t (43.7%) categories. Preservatives' production had the highest impacts on ADP-m (95.6%), AP (75.8%), EP-f (68.8%), and EP-m (42.5%) categories. Preservatives application had the highest impacts on the WDP category (37.5%). End-of-life operations had the highest impacts on GWP-t (50.7%) and GWP-b (50.0%) categories.

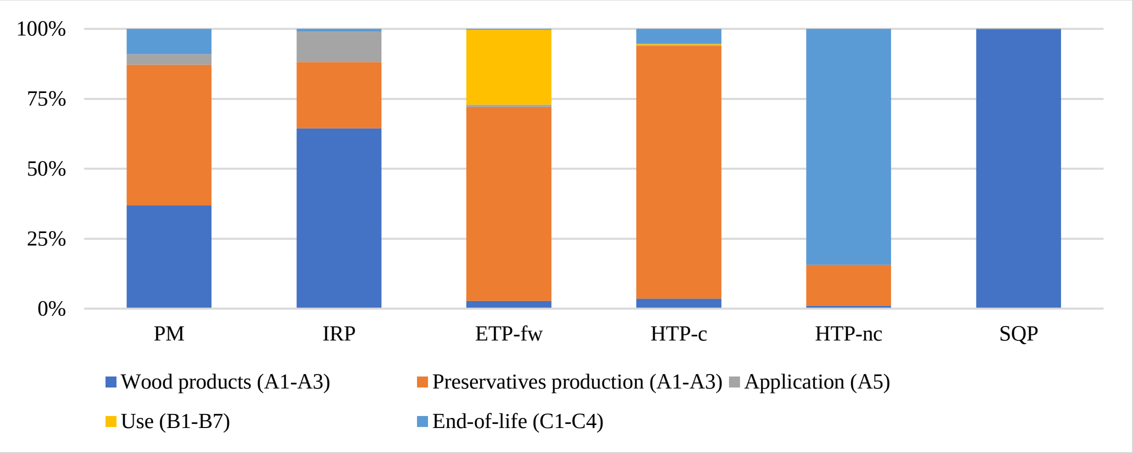

Figure 91 - Comparison of additional environmental impacts of life cycle operations of MP_PT scenario

For additional environmental impacts, preservatives production had the highest impacts on HTP-c (90.4%), ETP-fw (69.3%) and PM (50.3%). Wood products had the highest impacts on SQP (99.8%) and IRP (64.5%). For the HTP-nc category, the highest impacts were noted for end-of-life operations (84.3%).

A further analysis found that the impacts of the application of pressurised treatments on the majority of core and additional categories were mainly due to the copper oxide production operations. The highest influence of use phase was noted on the ETP-fw category (26.8%). A further analysis identified that the ETP-fw impacts of use phase were mainly due to copper emissions. The highest influence of the application phase was noted on the WDP (37.5%) category, followed by IRP (10.9%). Those impacts were mainly due to tap water and electricity production used for treatment application, respectively.

The core and additional impacts of Maritime pine with a surface treatment are shown in Figure 92 and in Figure 93, respectively.

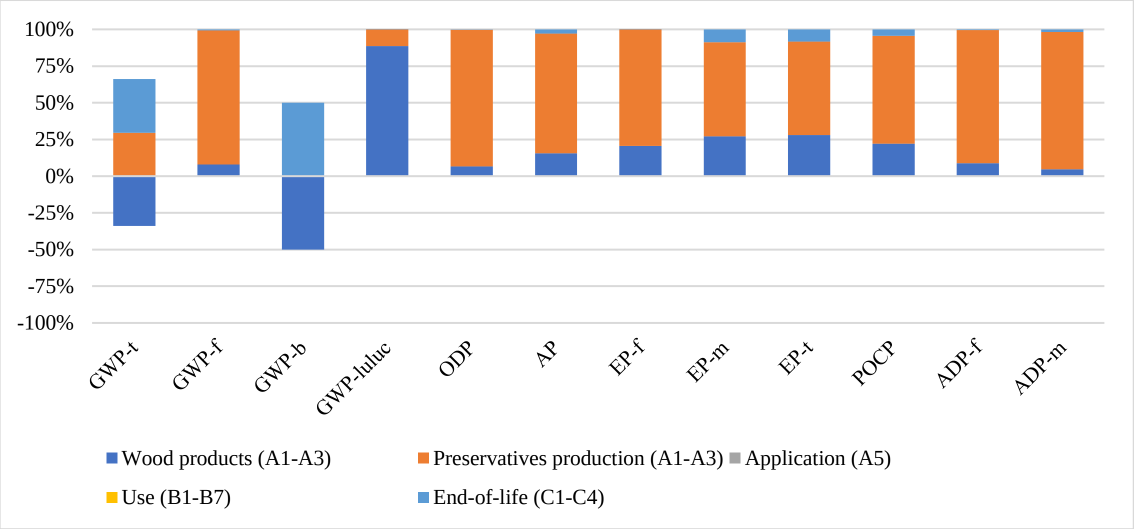

Figure 92 - Comparison of core environmental impacts of life cycle operations of MP_ST scenario

Preservatives’ production had the highest impacts on all core impact categories (between 63.6% and 93.4%), except for GWP-t, GWP-b, and GWP-luluc, where wood products represent 33.9%, 50%, and 88.7% of impact values, respectively. A further analysis identified that the preservatives production impacts were mainly due to the hazardous waste treatment and naphtha production.

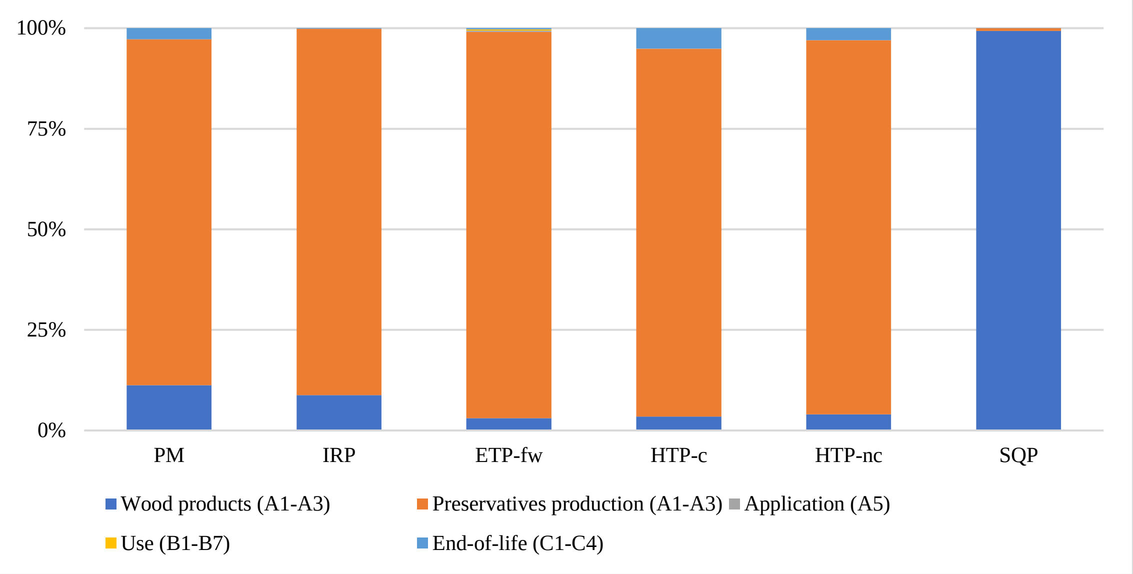

Figure 93 - Comparison of additional environmental impacts of life cycle operations of MP_ST scenario

Preservatives' production also had the highest impacts on PM (86.0%), IRP (91.1%), ETP-fw (96.0%), HTP-c (91.5%) and HTP-nc (93.0%) categories. Wood products had the highest impacts on the SQP (99.3%) category. A further analysis identified that the preservatives production impacts were mainly due to the hazardous waste treatment.

8.4.2 Comparison of various durability plans

For the same design project, different approaches can be considered to ensure the durability of wood elements. This section intends to compare the environmental impacts of four different durability plans of wood products. This comparison was made for Maritime pine wood and for a lifespan of 30 years. The durability plans compared were:

- Case 1: Surface treatment applied once, every two years,
- Case 2: Pressurised treatment applied once, every fifteen years (using the same wood elements),
- Case 3: Pressurised treatment applied once, every fifteen years (replacing the wood elements),
- Case 4: Combination of pressurised treatments (during fifteen years – one application) and surface treatment (during fifteen years – seven applications).

The core and additional environmental impacts of various scenarios are shown in Table Q-1 of Annex Q and compared in Figure 94 and in Figure 95, respectively.

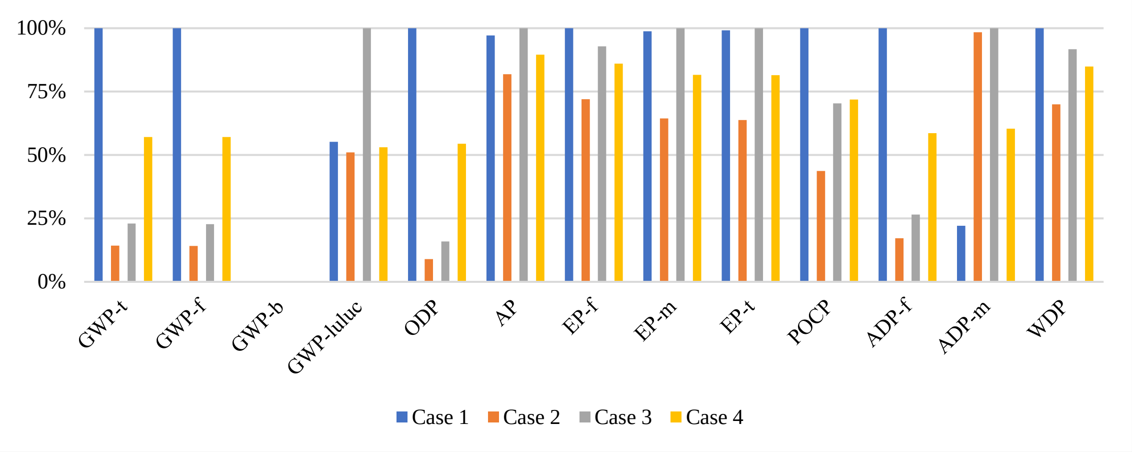

Figure 94 – Relative environmental impacts of core environmental impacts of various durability plans

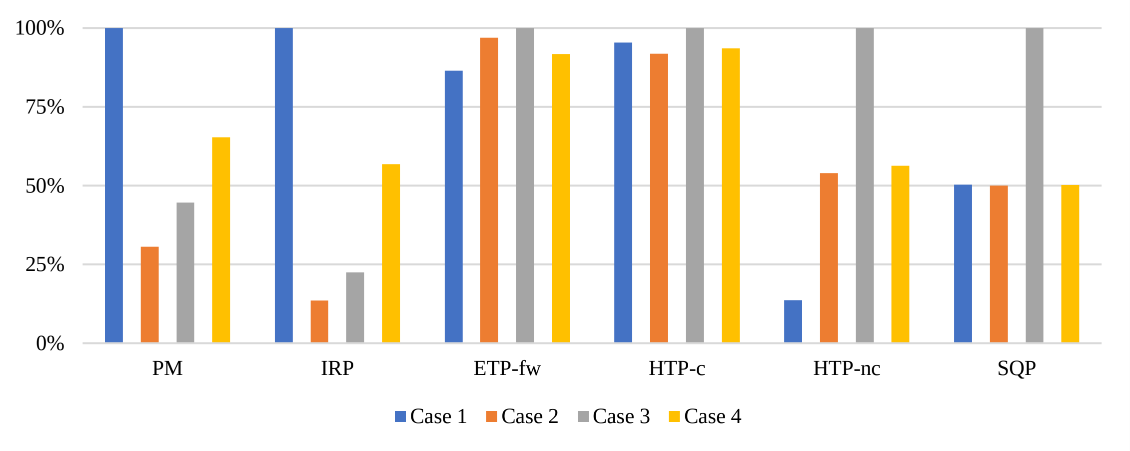

Figure 95 - Relative environmental impacts of additional environmental impacts of various durability plans

For the core and additional categories, Case 1 had the highest impacts on all categories, except for GWP-luluc, AP, EP-m, EP-t, ADP-m, ETP-fw, HTP-c, HTP-nc, and SQP, where Case 3 had the highest impacts. Case 2 had the lowest impacts on all categories, except for ADP-m ETP-fw, and HTP-nc, where Case 1 had the lowest impacts.

According to Figure 94 and Figure 95, for Maritime pine wood species, the pressurised treatment scenario without replacement of wood products (Case 2) led to lower impacts than the scenario that considers the replacement of wood elements (Case 3). The difference between both scenarios was mainly related to the amount of wood consumed. The scenario that considers the application of both treatment types (Case 4) had lower impact than the scenarios that consider the application of surface pressurised treatments with wood replacement (Case 3). Case 1 had higher impacts than Case 2 and Case 3 for the majority of the impact categories.

8.5 Conclusions

This chapter discussed the results presented in Chapter 7, compared those results with literature results, and compared the environmental impacts of different LCI modelling procedures. The discussion was performed at various levels: roundwood, structural products, structural floor solutions and durability solutions.

For roundwood, the discussion comprised the: i) comparison of results of this study with literature results, ii) comparison of environmental impacts per life cycle operation, iii) comparison of a volumetric and an economic allocation, and iv) comparison of different LCI methodologies.

The results of Maritime pine and Eucalyptus roundwood production were compared with those of Dias & Arroja (2012). This comparison found that the results obtained in this study were similar to the results obtained in literature. The highest difference of results was noted for the AP and EP categories and was a consequence of the high consumption of fertilizers of 1E and 2E scenarios. Maritime pine scenarios were also compared with the results of Ferreira *et al.* (2021). The results are similar for both studies, and, once more, the highest difference between results was due to the fertilising operations.

Stand establishment and tending, and logging, were the operations that had the highest influence on the majority of the environmental impacts of Portuguese forest management scenarios. The environmental impacts of stand establishment and tending are highly influenced by fertilising and power sawing operations. The diesel combustion had the highest influence on the environmental impacts of logging operations.

The use of an economic allocation on Portuguese forest management scenarios to model the production of roundwood and biomass increased the environmental impacts of roundwood products. This occurs because the price per cubic meter of roundwood and the volume of roundwood produced are higher than those of biomass.

The LCI of diesel spent during the machinery operations of forest management operations was determined with data available in the Ecoinvent database (Wernet *et al.*, 2016). This study compared the environmental impacts of this methodology with another one that used national databases. The comparison of results showed that the main differences between both scenarios were related to the emissions resulting from diesel production and combustion.

For structural products, the discussion comprised the: i) comparison of environmental impacts with ReVa, ii) comparison of environmental impacts assuming different allocation procedures, iii) comparison of environmental impacts of various life cycle operations, iv) comparison of results of various methodologies defined by mechanical grading allocation procedures, and v) comparison of environmental impacts of structural products by calculating bending strength and modulus of elasticity equivalent units.

The comparison of SW results with ReVa calculated in Chapter 2 showed that the environmental impact of various scenarios modelled in this study were within the standard deviation range of the EPD_SW_ReVa scenario, except for Maritime pine scenario on POCP and the Maritime pine, Eucalyptus and Cryptomeria scenarios on GWP. For GLT and LVL products, AP, EP, ADPE and ODP impact values were lower for ReVa than for results calculated by this study.

The comparison of various allocation procedures (volume, mass, economic) for Maritime pine sawnwood production identified that economic allocation led to the highest environmental impacts of sawnwood. In contrast, this procedure led to the lowest impacts of wood chips, sawdust and bark. The lowest impacts of sawnwood were noted for volume allocation. The highest impacts of sawdust, wood chips, and bark were noted for volumetric allocation. All types of allocation procedures compared (economic, massic and volumetric) had lower environmental impacts than the scenario that did not consider any type of allocation procedure.

For Maritime pine sawnwood production, the electricity and diesel production and combustion were the operations that had the highest influence on most environmental categories. Lubricant production had the highest impacts on the ADP-m category.

The environmental comparison of strength classes based on mechanical grading methodology showed that the highest strength classes had the highest impacts. The comparison of sawnwood products based on their bending strength and modulus of elasticity showed that Eucalyptus and Maritime pine had the highest and lowest impacts, respectively, for both equivalent units considered. The highest increase of relative impacts between comparison per cubic meter and per bending strength and modulus of elasticity units was noted for products with the lowest strength and stiffness properties. In contrast, the highest decrease was noted for products with the highest strength and stiffness properties.

For structural solutions, the discussion comprised the: i) comparison of the volume of different structural configurations, and ii) modelling procedures of energy recovery at the end-of-life. The structural configurations varied: the pre-sizing rules (height equal to length divided by 20, which was 200 mm (h=200 mm); height equal to three times the width (h=3*w); and height equal to two times the width (h=2*w)) and the supporting conditions (considering a middle span supporting beam).

The pre-sizing rule that led to the highest amount of volume was “h=2*w”. For the products with the highest strength classes, the h=3*w pre-sizing rule showed the lowest volumes. For those with the lowest strength classes, the h=200 mm pre-sizing rule was the scenario that had the lowest impacts. The middle span supported scenario had lower impacts than the scenario that assumed simply supported beams.

The modelling procedures of energy recovery at the end-of-life found that the structural solutions that have LVL had the highest impacts on the majority of the impact categories. The highest benefits of energy recovery were noted for the Eucalyptus and Maritime pine scenarios. The lowest benefits were noted for the I-Joists and LVL scenarios. The highest benefits were noted for the ETP-fw category.

For durability solutions, the discussion comprised the: i) comparison of environmental impacts of various life cycle operations, and ii) comparison of various durability scenarios using Maritime pine sawnwood. Preservative treatments production was the life cycle operation that had the highest influence on most environmental impacts, followed by sawnwood production.

For a lifespan of 30 years, the durability scenarios compared were: surface treatment applied once, every two years (Case 1); pressurised treatment applied once, every fifteen years (using the same wood elements) (Case 2), pressurised treatment applied once, every fifteen years (replacing the wood elements) (Case 3); combination of pressurised treatments (for the first fifteen years) and surface treatment (for the second fifteen years) (Case 4). For scenarios that only apply pressurized treatments, the one that assumed the replacement of wood elements (Case 3) led to the highest environmental impacts. The scenario that combines both types of treatment (Case 4) had lower impacts than the scenarios that only apply surface treatments (Case 1) and the scenario of pressurised treatment that replaces wood elements (Case 3).

9 CONCLUSIONS AND FUTURE RESEARCH

9.1 Conclusions

The present study intended to perform the LCA of wood-based products and solutions for different structural and durability applications. To achieve this main objective, intermediate ones have been defined: i) identification of the LCA procedures that must be followed to perform a LCA study of wood-based structural and durability solutions, ii) identification of the structural and durability design procedures of wood-based structures, iii) definition of the methods for comparison of products and solutions based on structural and durability equivalence units, iv) comparison of the environmental impacts of roundwood from various wood species, countries of origin and forest management practices, v) comparison of the environmental impacts of various structural products and solutions for a residential floor, vi) comparison of the environmental impacts of various durability solutions for a deck floor, vii) identification of the environmental hotspots during the life cycle of wood-based structural and durability solutions, and viii) analysis of the influence of the variation of LCA modelling procedure procedures on the environmental impacts of the referred solutions.

The objective of identifying the LCA procedures that must be followed to perform a LCA study of wood-based structural and durability solutions led to a review of the procedures given by European and Global standards for the LCA methodology. Additionally, the procedures followed by other LCA studies and EPDs that assessed wood-based products was also reviewed. These procedures were identified in Chapter 2 and were used to model the LCA of wood-based products and solutions performed in Chapters 5, 6, 7 and 8.

The objective of identifying the structural and durability design procedures of wood-based structures was achieved through a revision of the European standards that give the design rules and procedures (shown in Chapter 3). The design procedures identified were useful to define various methodologies (Chapter 4) to compare products and solutions based on structural and durability equivalent units. The review of structural design procedures found that the structural design of wood products requires a quantification of strength classes of wood elements through visual and/or mechanical methodologies. These were used to define two methodologies to quantify the environmental impacts of different strength classes (proposed in section 4.2). The structural design procedures identified in Chapter 3 were used to define the bending strength and modulus of elasticity equivalent units (presented in Section 4.3) and the structural equivalent functional unit (given in Section 4.4). The durability design procedures, also presented in Chapter 3, were used to define a durability equivalent functional unit (given in Section 4.5).

The comparison of the environmental impacts of roundwood ("forest management" level) analysed: i) various wood species: Maritime pine, Cryptomeria, Eucalyptus, Scots pine and Norway spruce; ii) various countries of origin: Portugal (for Maritime pine, Cryptomeria, Eucalyptus), Germany (for Scots pine and Norway spruce) and Sweden (for Scots pine and Norway spruce); and iii) various forest management models (for Maritime pine): planted, natural regeneration, and seeded. Combining various alternatives of wood species, country of origin and forest management models, various scenarios were defined. Chapter 5 defined the LCA procedures to follow, and the functional units and the system boundaries to consider for each scenario. Chapter 6 gave the LCI methodologies and data of various scenarios and Chapter 7 compared the environmental impacts. The comparison of various wood species showed that Eucalyptus and Cryptomeria scenarios had the highest and lowest impacts on the majority of the impact categories, respectively. For wood species from different origins (Sweden and Germany), the German scenario had higher impacts than the Swedish scenarios for both Spruce and Scots pine species on the majority of the impact categories. For Maritime pine scenarios, the natural regeneration scenario had the lowest impacts, and the seeded scenario had the highest impacts.

The comparison of the environmental impacts of various structural products ("production of structural products" level) was performed based on the: cubic meter of products (in Chapter 7), strength classes (Section 8.2.4.1), and bending strength and modulus of elasticity equivalent units (Section 8.2.4.2). The products compared were: GLT, LVL, and SW (for the same roundwood scenarios). Chapter 5 defined the LCA procedures followed, and the functional units and system boundaries considered for each scenario, and Chapter 6 gave the LCI methodologies and data of the various scenarios. Per cubic meter, LVL products had the highest impacts on the majority of the impact categories, followed by GLT. In contrast, Spruce sawnwood from Sweden was the scenario that had the lowest impacts on the majority of the impact categories. In terms of strength classes, the scenarios of sawnwood with the highest strength classes had higher environmental impacts than the scenarios with low strength classes. The comparison per bending strength and modulus of elasticity equivalent units showed that Eucalyptus and Maritime pine had the highest and lowest ETP-fw impacts, respectively.

In terms of structural solutions ("building solutions" level) the environmental impacts of GLT, LVL, SW (for the same roundwood scenarios), and I-Joists, were compared. The functional equivalent unit used for comparison was defined in Chapter 4. Chapter 5 defined the LCA procedures followed, and the functional units and system boundaries for each scenario. Chapter 6 gave the LCI methodologies and data of various scenarios and

Chapter 7 compared the environmental impacts. At the end-of-life, two alternatives were modelled: incineration and landfill. For the full life cycle, LVL had the highest impacts on the majority of the impact categories for both end-of-life alternatives, followed by I-Joists made with LVL. Maritime pine sawnwood had the lowest impacts on the majority of the impact categories for both end-of-life alternatives, followed by Spruce from Sweden. The benefits of considering the landfill or incineration at the end-of-life varied according to categories. For the GWP-t, EP-t, ADP-m, WDP, HTP-c, HTP-nc and SQP categories, the landfill scenario had higher impacts than incineration, and for the GWP-f, ODP, EP-f, EP-m, and ETP-fw categories, the incineration scenario had higher impacts than landfill.

The comparison of the environmental impacts of various durability solutions for a deck floor ("building solutions" level) varied the: i) wood species (Maritime pine, Cryptomeria, Eucalyptus, Scots pine and Norway spruce), ii) treatment methodology (surface and pressurised), and iii) treatment product. Chapter 4 gave the equivalent functional unit used for the comparison of various scenarios. Chapter 5 defined the LCA procedures followed, and the functional units and the system boundaries of each scenario. Chapter 6 gave the LCI methodologies and data of various scenarios and Chapter 7 compared their environmental impacts. Cryptomeria with surface treatments had the lowest impacts on the majority of the categories, followed by Cryptomeria with pressurised treatments. Maritime pine with surface treatments had the highest impacts on the majority of the impact categories.

The identification of the environmental hotspots during the life cycle of wood-based structural and durability solutions was performed in Chapter 8. For roundwood production (forest management): fertilising and power sawing were the operations that had the highest influence on the majority of the environmental categories. During sawnwood production (Maritime pine): diesel production and combustion and electricity production were the operations that had the highest influence on the majority of the environmental categories. For durability solutions, the highest influence on life cycle was noted for the production of preservative products.

The analysis of the influence of LCA variables on environmental impacts of various solutions was performed in Chapter 8. For roundwood, the environmental impacts of Portuguese scenarios calculated in Chapter 7 were compared with various alternative scenarios that varied the: i) allocation procedure (economic), and ii) LCI database for modelling procedures of diesel, petrol and lubricant consumption. The results showed that the scenario that performed an economic allocation had higher impacts than the scenario that performed a volume allocation. The highest difference between both LCI databases was noted for the GWP-luluc, EP-f, PM and HTP-c categories and was mainly due to the differences on diesel and petrol production and combustion process.

In terms of structural products, the LCA modelling procedures varied the type of allocation (volume, mass and economic). The results showed that the highest impacts of sawnwood were noted for economic allocation, followed by massic allocation. The lowest impacts of coproducts (sawdust, wood chips and bark) were noted for economic allocation, followed bymassic allocation, except for wood chips, where the second lowest impacts were noted formassic allocation.

9.2 **Future research**

From the work performed, it was possible to identify some aspects that could be the subject of further research in the future, as well as some other topics that were not addressed in this thesis and that deserve to be pursued further.

The scope of this study was related to the quantification of the environmental impacts of various wood-based solutions. In a scenario where this study would be applied in the industry (by engineers or architects), other variables important for construction owners, such as economic impacts, should be considered. Therefore, it is recommended to extend the scope of this study to quantify the economic impacts through the Life Cycle Costs (LCC) methodology.

The productivity of various Portuguese forest management models was given by the mean values of various case studies distributed across the country. According to the forest management company that monitored those case studies, the productivity of a forest land depends on the operations performed during the growth of trees, topographic factors, climatic and meteorological factors, land-use and vegetation, fire risk, etc. For future research, the calculation of the productivity of national wood species across the country for the various forest management models and the various location dependent variables is recommended. Therefore, it will be possible to calculate and compare the environmental impacts of different forest management models from different sources and, consequently, provide a better support to environmental decisions made by the industry.

The LCA of structural and durability solutions excluded the environmental impacts of construction accessories of wood-based products such as connectors. Some studies indicated that connectors, usually made of steel, can negatively influence the environmental impacts of the full solutions. Therefore, it is recommended that future studies calculate the environmental impacts of connectors and analyse their influence on the whole structural solution.

Some wood-based products require the use of adhesives. There is a large variety of adhesives that vary their chemical compositions. To reduce the environmental impacts of wood-based products, future studies may compare the environmental impacts of various adhesives. This comparison should be made by considering a functional equivalence defined based on the mechanical behaviour of glued products.

This study considered that the structural loads were supported by beams. However, in the last years, structural products which have emerged are planar (e.g. CLT) and can overcome some of the disadvantages of traditional timber products. Thus, it is recommended that this type of products be included in future comparisons of wood-based structural products and solutions.

The methods developed in this study were applied to flooring solutions (interior and exterior): however, wood products can also have other types of applications (walls, roofs, columns, etc.). Therefore, it is recommended that these methodologies are applied to other types of construction solutions.

This study followed a static LCA methodology. Recent methodologies have been developed, which take into account the dynamic iterations of LCA over time (Levasseur *et al.*, 2010). A dynamic LCA approach intends to improve the accuracy of LCA by addressing the inconsistency of temporal and spatial assessment. This methodology has been applied to calculate the environmental impacts of wood products by other studies (Bergman et al., 2012; Caldas et al., 2019; Dackermann et al., 2016; Göswein et al., 2021; Hoxha et al., 2020; Pittau et al., 2018). Therefore, it is recommended to be studied the dynamic interactions of wood-based products produced in Portugal.

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APPENDIXES

Annex A – Data collected for Native LCA methodology

Table A. 1 - General data collected from SW EPDs for NativeLCA methodology

No.	EPD programme	Country	Year	Sampling Procedure	Companies	Functional unit	Density	Moisture content (%)	LCA stages considered
SW 1	EPD Norge	Norway	2014	Group of manufacturers	Members of N. W. I. F.	1 m^3 of sawn dried timber	450 kg/m^3	15	A1-A3; C2-C4; D
SW 2						1 m^3 of planed structural timber of spruce and pine	420 kg/m^3	17	A1-A3; A4-A5; B2-B7; C1-C4; D
SW 3	IBU	Italy	2016	Individual EPD	Rubner Holding AG S.p.A	1 m³ of holzius solid wood slab elements	495 kg/m^3	13	A1-A3; C3; D
SW 4ª		Germany	2011	Group of manufacturers	Überwachungsgemeinschaft Konstruktionsvollholz.	1 m³ of structural timber	490 kg/m^3	10,7	A1-A3; C2-C4; D
SW 4b						1 m³ of KVH® structural timber	493 kg/m^3	10,7	A1-A3; C2-C4; D
SW 5		Germany	2012	Individual EPD	Fritz EGGER GmbH & Co. OG	1 m³ of EGGER sawn timber dried	507 kg/m^3	15	A1-A3; D
SW 6						1 m³ of EGGER sawn timber green	740 kg/m^3	70	A1-A3; D
SW 7						1 m³ of EGGER sawn timber planed	489 kg/m^3	15	A1-A3; D
SW 8		Austria	2016	Individual EPD	Rubner Holding AG S.p.A.	1 m³ of solid structural timber [KVH]	465 kg/m^3	10	A1-A3; C3; D
SW 9ª	Environdec	Australia	2015	Group of manufacturers	Members of Forest and Wood Products Australia Ltd	1 m^3 of sawn kiln-dried softwood	551 kg/m^3	12	A1-A3; C3; C4; D
SW 9b						1 m^3 of dressed kiln-dried softwood	551 kg/m^3	12	A1-A3; C3; C4; D
SW 10a						1 m^3 of rough-sawn, kiln-dried hardwood	735 kg/m^3	10	A1-A3; C3; C4; D
SW 10b						1 m^3 of dressed, kiln-dried hardwood	735 kg/m^3	10	A1-A3; C3; C4; D
SW 10c						1 m^3 of rough-sawn, green hardwood	768 kg/m^3	26	A1-A3; C3; C4; D
SW 11	BRE	United Kingdom	2013	Group of manufacturers	Members of Wood for Good	1 m^3 of fresh sawn softwood based on the UK consumption mix	672 kg/m^3	60	A1-A3; A4-A5; C1-C4; D
SW 12			2013			1 m^3 of kiln dried hardwood	698 kg/m^3	12	A1-A3; A4-A5; C1-C4; D
SW 13			2014			1 m^3 of kiln dried planed or machined sawn timber used as structural timber	479 kg/m^3	15	A1-A3; A4-A5; B1-B7; C1-C4; D
SW 14			2013			1 m^3 of planed kiln dried softwood	482 kg/m^3	15	A1-A3; A4-A5; C1-C4; D

Table A. 2 - General data collected from GLT, LVL and IJ EPDs for NativeLCA methodology

No.	EPD programme	Country	Year	Sampling Procedure	Companies	Functional unit	Density	Moisture content (%)	LCA stages considered
GL 1	EPD Norge	Swedish	2016	Individual EPD	Moelven Töreboda AB	1m^3 of glulam	430 kg/m^3	14	A1-A3; A4
GL 2		Norway	2014	Individual EPD	Solarminering AS	1m^3 of glulam	470 kg/m^3	12,5	A1-A3; A4-A5; C1-C4; D
GL 3		Norway	2015	Individual EPD	Sokolsky DOK	1 m^3 of glued laminated timber with packaging.	505 kg/m^3	12	A1-A3; A4
GL 4	IBU	Austria	2016	Individual EPD	Rubner Holding AG S.p.A	1 m^3 of glued laminated timber	464 kg/m^3	10	A1-A3; C3; D
GL 5[a]	Environdec	Australia	2015	Group of manufacturers	Members of FWPA	1 m^3 of untreated softwood glulam	621 kg/m^3	12	A1-A3; C3-C4; D
GL 5b						1 m^3 of hardwood or cypress pine glulam	674 kg/m^3	10,5	A1-A3; C3-C4; D
GL 6	BRE	United Kingdom	2013	Group of manufacturers	Members of Wood for Good	1 m^3 of glued laminated timber	490 kg/m^3	12	A1-A3; A4-A5; C1-C4; D
GL 7	IBU	Germany	2011	Group of manufacturers	Members of Studiengemeinschaft Holzleimbau e.V	1 m^3 glued laminated timber	508 kg/m^3	10,5	A1-A3; C2-C4; D
GL 8	IBU	Germany	2017			1 m^3 Duobalken®, Triobalken® (glued solid timber)	476 kg/m^3	12	A1-A3; A5; C2-C3; D
GL 9	IBU	Switzerland	2017	Individual EPD	Schilliger Holz AG	1 m^3 SchilligerGlulam	424 kg/m^3	12	A1-A3; A4-A5; C2-C4; D
IJ 1	EPD Norge	Sweden	2014	Individual EPD	Masonite Beams AB	1 LM (linear metre) I-beam H300	3,3 kg/lm	-	A1-A3; A4-A5; C1-C4; D
IJ 2	Environdec	United Kingdom	2016	Individual EPD	James Jones & Sons Ltd	1 LM (linear metre) of average joist	4,1 kg/lm	15	A1-A3
IJ 3	Metsä Wood	United Kingdom	2013	Individual EPD	Metsä Wood	1 kg of product	3,8 kg/lm	12,5	A1-A3
IJ 4	INIES	France	2012	Group of manufacturers	APIBOIS companies	1 LM (linear metre) of 395 / 60x90 element	7,1 kg/lm	15	A1-A3; A4-A5; C1-C4; D
IJ 5						1 LM (linear metre) of 393 / 94×94 element	11,4 kg/lm	15	A1-A3; A4-A5; C1-C4; D
LVL 1	BRE	United Kingdom	2013	Group of manufacturers	Members of Wood for Good	1 m^3 of LVL	488 kg/m^3	12	A1-A3; A4-A5; C1-C4; D
LVL 2	Metsä Wood	Finland	2013	Individual EPD	Metsä Wood	1 m^3 of product	475 kg/m^3	9	A1-A3

Table A. 3 - Consistency data collected from SW EPDs for NativeLCA methodology

No.	Cut-off rules	Allocation	Background data	Temporal repress.	Geographical coverage	Technological Level
SW 1	<1% raw materials and flows are not included	According to EN 15804:2012 (mass and volume). When the amount of co-product is reduced an economical allocation is performed	Ecoinvent v2.2 and ELCD 3.0	2013	Companies of NWIF	Typical technology (TT) of Norway
SW 2						
SW 3	<1% raw materials and flows are not included	EPD considers the inherent properties of wood (carbon content and primary energy content) and relies on its physical relations.	Gabi 8	2016	1 Production site (PS) in Italy	TT of company
SW 4a	<1% raw materials and flows are not included	The allocations performed comply with the requirements outlined in EN 15804:2012	Gabi 4	2008-2010	KVH companies	TT of all members
SW 4b						
SW 5	All data from the operational data collection, i.e., all input materials used for formulation, which used thermal and electrical energy, are considered.	This allocation is made for all process steps by volume (excluding the grading process, which is based onmassic allocation).	Gabi 6	2012	1 PS in Germany	TT of Germany
SW 6						
SW 7						
SW 8	<1% raw materials and flows are not included	EPD considers the material inherent properties of wood (carbon content and primary energy content) and relies on its physical relations.	Gabi 8	2016	1 PS in Austria	TT of Austria
SW 9a	Environmental impacts relating to personnel, infrastructure, and production equipment not directly consumed in the process are excluded from the system boundary	Allocation recommended by Gabi database	Gabi 2017	2013-2015	5 Australian companies	TT of Australia
SW 9b						
SW 10a			Gabi 2017	2013-2015	6 Australian companies	TT of Australia
SW 10b						
SW 10c						
SW 11	-	Sawmill energy, fuel and material inputs and outputs were allocated based on price. The others are allocated by physical properties of wood	Gabi 6	2012	Wood for Good members in UK	TT of UK
SW 12						
SW 13	All raw materials and energy inputs directly related with production have been included	Economic basis allocation	Gabi 2016	2014	Wood for Good members in UK	TT of UK
SW 14	-	Sawmill energy, fuel and material inputs and outputs were allocated based on price. The others are allocated by physical properties of wood	Gabi 6	2012	Wood for Good members in UK	TT of UK

Table A. 4 - Consistency data collected from GLT, LVL and IJ EPDs for NativeLCA methodology

No.	Cut-off rules	Allocation	Background data	Temporal repress.	Geographical coverage	Technological level
GL 1	<1% raw materials and flows are not included	The allocation is made in accordance with the provisions of EN 15804. The first approach for allocation of environmental impact ismassic allocation. When co-product with low value appears, an economical allocation is stipulated.	Gabi 2016	2012	1 PS in Sweden	TT of Sweden-
GL 2			Ecoinvent v2.2	2012	1 PS in Norway	TT of Norway-
GL 3			Ecoinvent v3.3	2015	1 PS in Austria	TT of Austria -
GL 4		The allocation considers the material inherent properties of wood (carbon content and primary energy content.	Gabi 8	2016	PSs: 2 in Italy and 2 in Austria	TT of company-
GL 5a	Environmental impacts relating to personnel, infrastructure, and production equipment not directly consumed in the process are excluded from the system boundary	The allocation of refinery is based on mass and net calorific values. The allocation of energy consumption is based on economic values. The allocation of materials and chemicals are based on mass values and co-products allocation is based on economic values.	Gabi 2017	2015-2016	4 Australian companies	TT of Australia -
GL 5b				2015-2017	4 Australian companies	TT of Australia -
GL 6	-	Sawmill energy, fuel and material inputs and outputs were allocated based on price. The others are allocated by physical properties of wood	Gabi 6	2012	Wood for Good members in UK	TT of UK
GL 7	<1% raw materials and flows are not included	The allocations carried out comply with EN 15804:2012 and EN 16485:2014.	Gabi 4	2008-2010	50% of menbers of Studiengemeinschaft Holzleimbau e.V	TT of Germany
GL 8			Gabi 6	2008-2010		
GL 9			Ecoinvent v2.2	2016	1 PS in Germany	TT of Switzerland
IJ 1	<1% raw materials and flows are not included	Allocation is performed in accordance to NS-EN 15804:2012. In the production chain of wood, economic allocation is performed.	Ecoinvent 2.2 and ELCD 3.0	2013	1 PS in Sweden	TT of Sweden
IJ 2	Contributions cut-off from Ecoinvent. 3 processes used within this model have been excluded.	Calculations cover a minimum of 95% of total inflows to the upstream and core module.	Ecoinvent 3	2016	1 PS in UK	TT of UK
IJ 3	-	-	GaBi 6 and LIPASTO.	2013	1 PS in UK	TT of UK
IJ 4	All material and energy fluxes known to be capable of causing significant emissions to air, water or soil have been included.	The waste generated during manufacturing and recovered outside the system has been assigned as co-products, with an allocation of the impacts of the processes that generated them 100% to the studied product.	Ecoinvent 2.2	2012	APIBOIS companies in France	TT of France
IJ 5			Ecoinvent 2.2	2012	APIBOIS companies in France	TT of France
LVL 1	-	Sawmill energy, fuel and material inputs and outputs were allocated based on price. The others are allocated by physical properties of wood	Gabi 6	2012	Wood for Good members in UK	TT of UK
LVL 2	-	-	GaBi 6 and LIPASTO.	2013	1 PS in UK	TT of UK

Table A. 5 - Representativeness data collected from SW EPDs for NativeLCA methodology

No.	Biogenic carbon considered?	Carbon account methodology	Amount of biogenic carbon by FU ($kgCO_2/m^3$)	Packing considered?	Species	Glues	Amount of glue [%]	Height [m]	Width [m]	Length [m]	Structural class (defined)
SW 1	Yes	EN 16449	715	Yes	Pine and Spruce	-	-	-	-	-	-
SW 2	Yes		660	Yes	Pine and Spruce	-	-	-	-	-	C24
SW 3	Yes	-	-	Yes	Spruce; Pine and Larch	-	-	-	0 – 0.35	0 - 13.5	C24
SW 4a	Yes	-	990	Yes	Spruce, Fir, Pine, Larch or Douglas fir	-	-	0.6 - 0.14	0.1 - 0.24	0 - 13	C24
SW 4b	Yes	-	990	Yes		PUR and MUF	-	0.6 - 0.14	0.1 - 0.24	0 - 13	C24
SW 5	Yes	-	-	Yes	Spruce and Pine	-	-	0.012 - 0.15	0.03 - 0.35	2 - 5.4	-
SW 6	Yes	-	-	Yes		-	-	0.012 - 0.15	0.03 - 0.35	2 - 5.4	-
SW 7	Yes	-	-	Yes		-	-	0.012 - 0.15	0.03 - 0.35	2 - 5.4	-
SW 8	Yes	-	-	Yes	Spruce; Pine, Larch, and Douglas fir	MUF	-	0.06 - 0.28	0.06 - 0.28	0 - 50	C24
SW 9a	Yes	EN 16449	887	Yes	Pinus radiata; Araucaria cunninghami; Pinus Pinaster and Pinus elliottii; and Pinus caribaea	-	-	0.035 - 0.09	0.042 - 0.29	-	-
SW 9b	Yes		882	Yes		-	-	0.035 - 0.09	0.042 - 0.29	-	-
SW 10a	Yes		1100	Yes	Australian native hardwood species	-	-	-	-	-	-
SW 10b	Yes		1060	Yes		-	-	-	-	-	-
SW 10c	Yes		1000	Yes		-	-	-	-	-	-
SW 11	Yes		-	-	Scots pine and European spruce.	-	-	-	-	-	-
SW 12	Yes		-	-	Oak; beech; ash; Poplar	-	-	-	-	-	-
SW 13	Yes		712	Yes	Spruce, Pine, Larch and Douglas Fir.	-	-	-	-	-	-
SW 14	Yes		-	-	Pine and Spruce	-	-	-	-	-	-

Table A. 6 - Representativeness data collected from SW EPDs for NativeLCA methodology

No.	Biogenic carbon considered?	Carbon account methodology	Amount of biogenic carbon by FU ($kgCO_2/m^3$)	Packing considered?	Species	Glues	Amount of glue [%]	Height [m]	Width [m]	Length [m]	Structural class (defined)
GL 1	Yes	49 % of dry matter of wood is carbon	804	Yes	Spruce	MUF	1,0	-	-	-	-
GL 2	Yes	EN 16449	755	Yes	Spruce and pine	LIM	1,5	-	-	-	-
GL 3	Yes	EN 16449	808	Yes	Pine and Spruce	MUF and hardener	1,1	0.200	0.120	12	-
GL 4	Yes	-	-	Yes	Spruce, Pine, Larch and Douglas fir	MUF; Melanin and EPI	1,0 - 2,5	-	-	-	GL 24 h
GL 5a	Yes	EN 16449	1017	Yes	Pinus elliottii; Pinus radiata; Pinus caribaea; Cypress pine	PRF and PUR	0,8	-	-	-	-
GL 5b	Yes	EN 16449	1118	Yes	Eucalyptus delegatensis; Eucalyptus regnans, Spotted gum; Tasmanian oak	PRF and PUR	0,3	-	-	-	-
GL 6	Yes	EN 16449	-	-	UK consumption mix	MUF; PRF; PUR	2,1	-	-	-	-
GL 7	Yes	-	1049	Yes	Spruce, Fir, Pine, Larch and Douglas fir	MUF; PRF; PUR	2,1	0.100 – 2.400	0.060 – 0.240	0 - 50	GL 24 h
GL 8	Yes	-	932	Yes	Various species of wood	MUF; PRF; EPI and PUR	1,0	0.280	0.280	14	C18, C24, C30
GL 9	Yes	-	-	Yes	Spruce and Silver fir (Pine, Larch and Douglas fir in small proportions)	PUR	0,9	0.080 – 2.000	0.100 – 0.280	18	GL24, GL28, GL32 [h/c]
IJ 1	Yes	EN 16449	5,23	Yes	-	-	-	-	-	-	C30+OSB/3
IJ 2	Yes	PAS 2050 (SimaPro)	4,43	Yes	-	PUR	1,5	-	-	-	C24+OSB/3
IJ 3	Yes	-	3,89	Yes	-	-	-	-	-	-	LVL+OSB/3
IJ 4	Yes	EN 16449	9,00	Yes	-	UF	-	-	-	-	C24+OSB/3
IJ 5	Yes	EN 16449	14,7	Yes	-	PUR	-	-	-	-	C24+C24
LVL 1	Yes	EN 16449	-	-	-	PF; PRF; PUR	2,5	0,030-0,090	0,045	12	-
LVL 2	Yes	-	789	Yes	-	PF; MF	-	-	-	-	-

Table A. 7 – Environmental impacts of SW, GLT, LVL and IJ EPDs used for ReVa calculation

EPD	**Functional Unit [F.U.]**	**Density [kg/F.U.]**	**Sampling**	**GWP [kg CO$_2$ - Eq.]**	**ODP [kg CFC11 - Eq.]**	**POCP [kg ethene - Eq.]**	**AP [kg SO$_2$ - Eq.]**	**EP [kg PO$_2^{3-}$ - Eq.]**	**ADPM [kg Sb - Eq.]**	**ADPE [MJ]**	**PE-Re [MJ]**	**PE-Nre [MJ]**
SW1	m^3	450	Group	-6.72E+02	5.51E-06	2.03E-03	3.39E-01	7.52E-02	9.48E-05	6.23E+02	9.68E+03	6.85E+02
SW2	m^3	420	Group	-6.07E+02	6.60E-06	2.65E-02	4.10E-01	8.99E-03	1.13E-04	7.82E+02	9.77E+03	9.02E+02
SW3	m^3	495	Individual	-7.34E+02	6.88E-11	6.95E-02	4.34E-01	8.06E-02	5.63E-05	9.48E+02	1.02E+04	1.06E+03
SW4a	m^3	490	Group	-7.77E+02	2.01E-06	2.94E-02	1.48E-01	3.20E-02	2.63E-04	3.01E+02	8.84E+03	3.69E+02
SW4b	m^3	490	Group	-7.34E+02	6.88E-11	6.95E-02	4.34E-01	8.06E-02	5.63E-05	9.48E+02	1.02E+04	1.06E+03
SW5	m^3	507	Individual	-7.84E+02	4.97E-10	8.25E-02	2.42E-01	4.93E-02	1.42E-05	3.18E+02	9.49E+03	3.30E+02
SW6	m^3	740	Individual	-7.79E+02	3.05E-10	5.71E-03	1.18E-01	2.73E-02	3.62E-06	2.41E+02	8.15E+03	2.50E+02
SW7	m^3	489	Individual	-7.55E+02	4.54E-10	8.24E-02	2.53E-01	5.12E-02	1.39E-05	3.21E+02	9.31E+03	3.32E+02
SW8	m^3	465	Individual	-6.74E+02	9.26E-11	1.06E-01	1.11E+00	2.22E-01	7.41E-05	1.12E+03	1.29E+04	1.25E+03
SW9a	m^3	551	Group	-7.60E+02	3.93E-11	5.51E-01	7.99E-01	2.16E-01	6.39E-05	1.61E+03	1.18E+04	1.61E+03
SW9b	m^3	551	Group	-6.99E+02	4.72E-11	6.80E-01	1.10E+00	2.75E-01	7.86E-05	2.25E+03	1.23E+04	2.26E+03
SW10a	m^3	735	Group	-8.88E+02	7.42E-11	3.10E+00	1.79E+00	4.19E-01	7.84E-06	2.50E+03	1.35E+04	2.51E+03
SW10b	m^3	735	Group	-7.31E+02	8.92E-11	3.88E+00	2.54E+00	5.65E-01	1.14E-05	3.83E+03	1.38E+04	3.84E+03
SW10c	m^3	768	Group	-8.51E+02	6.50E-11	2.68E+00	1.45E+00	3.52E-01	5.99E-06	1.80E+03	1.14E+04	1.81E+03
SW11	m^3	672	Group	-7.13E+02	1.93E-09	1.89E-02	3.48E-01	6.60E-02	1.51E-06	9.34E+02	8.12E+03	1.04E+03
SW12	m^3	698	Group	-8.78E+02	3.70E-08	5.95E-01	1.13E+00	1.48E-01	1.82E-05	2.53E+03	1.16E+04	2.84E+03
SW13	m^3	479	Group	-7.12E+02	2.52E-09	4.53E-02	6.44E-01	1.26E-01	5.13E-06	1.42E+03	1.07E+04	1.57E+03
SW14	m^3	482	Group	-6.46E+02	4.06E-09	6.38E-02	7.55E-01	1.31E-01	1.05E-05	1.75E+03	9.14E+03	2.13E+03
GL1	m^3	430	Individual	-6.56E+02	9.90E-07	4.20E-02	3.80E-01	8.70E-02	3.30E-05	8.67E+02	1.07E+04	1.64E+03
GL2	m^3	470	Individual	-6.30E+02	1.59E-05	5.86E-02	7.03E-01	2.37E-01	2.49E-04	1.93E+03	1.03E+04	2.42E+03
GL3	m^3	505	Individual	-7.13E+02	2.39E-05	9.36E-02	1.07E+00	1.56E-01	1.90E-03	3.10E+03	1.03E+04	3.28E+03
GL4	m^3	464	Individual	-6.46E+02	2.56E-05	1.03E-01	8.40E-01	1.70E-01	1.01E-04	1.34E+03	1.13E+04	1.50E+03
GL5a	m^3	621	Group	-6.12E+02	4.02E-10	8.12E-01	1.80E+00	3.78E-01	1.51E-04	4.96E+03	1.38E+04	4.98E+03
GL5b	m^3	674	Group	-4.08E+02	1.57E-10	4.37E+00	3.41E+00	6.87E-01	5.00E-05	6.14E+03	1.27E+04	6.16E+03
GL6	m^3	490	Group	-4.88E+02	1.66E-08	8.90E-02	1.03E+00	1.82E-01	8.42E-05	3.86E+03	1.04E+04	4.76E+03
GL7	m^3	508	Group	-7.55E+02	5.13E-06	2.42E-01	6.14E-02	4.45E-02	5.37E-04	8.80E+02	9.20E+03	1.06E+03
GL8	m^3	476	Group	-7.16E+02	4.08E-07	5.72E-02	2.74E-01	6.63E-02	7.03E-04	7.19E+02	9.03E+03	8.03E+02
GL9	m^3	424	Individual	-6.15E+02	5.24E-06	1.23E-01	3.94E-01	8.93E-02	2.20E-05	1.10E+03	8.80E+03	1.94E+03
IJ1	m.l.	3,32	Individual	-3.42E+00	1.78E-07	1.00E-03	8.14E-03	1.67E-03	4.11E-06	3.61E+01	9.98E+01	4.47E+01
IJ2	m.l.	4,10	Individual	-2.78E+00	1.81E-07	8.45E-04	1.03E-02	2.73E-03	4.51E-06	2.49E+01	5.77E+01	2.80E+01
IJ3	m.l.	3,81	Individual	-4.57E+00	4.00E-08	7.62E-04	7.62E-03	1.52E-03	4.31E-06	2.30E+01	9.60E+01	2.66E+01
IJ4	m.l.	7,10	Group	-7.52E+00	2.63E-07	1.34E-03	1.81E-02	3.20E-03	5.16E-06	5.68E+01	1.43E+02	8.52E+01
IJ5	m.l.	11,40	Group	-1.46E+01	3.11E-07	8.92E-04	2.39E-02	3.74E-03	2.74E-06	4.12E+01	2.10E+02	6.01E+01
LVL1	m^3	488	Group	-5.37E+02	1.90E-08	1.05E-01	1.15E+00	1.71E-01	5.81E-05	3.54E+03	1.06E+04	5.20E+03
LVL2	m^3	475	Individual	-6.55E+02	1.92E-08	9.20E-02	1.08E+00	2.20E-01	8.00E-04	2.61E+03	1.43E+04	3.08E+03

Annex B – Design verifications for SW, GLT, LVL and IJ products

Table B. 1 – Design verifications of SW softwood products

Verifications				**units**	**C18**	**C24**	**C30**	**C35**	**C40**
ULS	Bending		stress	[MPa]	7.73	9.45	10.27	11.2	12.0
			strength	[MPa]	10.7	14.2	17.77	20.7	23.7
	Shear		stress	[MPa]	0.58	0.70	0.77	0.84	0.89
			strength	[MPa]	1.90	2.37	2.37	2.37	2.37
	Compression perpendicular to the grain		stress	[MPa]	0.52	0.63	0.68	0.75	0.80
			strength	[MPa]	1.63	1.85	2.00	2.07	2.15
SLS	Deflection	Short term	deflection	[mm]	9.93	9.93	9.89	9.98	9.9
			limit	[mm]	10	10	10.00	10	10.0
		Long term	deflection	[mm]	13.4	13.3	13.29	13.4	13.3
			limit	[mm]	17.8	17.8	17.78	17.8	17.8
	Vibration	Vertical deflection	w/F	[mm/kN]	1.24	1.24	1.24	1.25	1.2
			a	[mm/kN]	1.5	1.5	1.50	1.5	1.5
		Unit impulse velocity response	ν	[m/Ns^2]	0.02	0.02	0.02	0.02	0.0
			$b^{(f1\zeta-1)}$	[m/Ns^2]	0.03	0.04	0.04	0.04	0.0

Table B. 2 – Design verifications of SW hardwood products

Verifications				**units**	**D24**	**D30**	**D35**	**D40**
ULS	Bending		stress	[MPa]	8.6	9.39	10.3	11.2
			strength	[MPa]	14.2	17.8	20.7	23.7
	Shear		stress	[MPa]	0.64	0.70	0.77	0.8
			strength	[MPa]	2.37	2.37	2.37	2.4
	Compression perpendicular to the grain		stress	[MPa]	0.57	0.63	0.69	0.7
			strength	[MPa]	5.78	5.92	6.00	6.1
SLS	Deflection	Short term	deflection	[mm]	9.96	9.88	9.92	10.0
			limit	[mm]	10	10	10	10.0
		Long term	deflection	[mm]	13.4	13.3	13.4	13.4
			limit	[mm]	17.8	17.8	17.8	17.8
	Vibration	Vertical deflection	w/F	[mm/kN]	1.23	1.22	1.23	0
			a	[mm/kN]	1.5	1.5	1.5	1.5
		Unit impulse velocity response	ν	$[m/Ns^2]$	0.02	0.02	0.02	0
			$b^{(f1\zeta-1)}$	$[m/Ns^2]$	0.03	0.03	0.03	0

Table B. 3 – Design verifications of GLT products

Verifications				**units**	**GL 24 h**	**GL 28 h**	**GL 32 h**
ULS	Bending		stress	[MPa]	9.82	10.9	12.2
			strength	[MPa]	16.3	18.9	21.7
	Shear		stress	[MPa]	0.73	0.81	0.91
			strength	[MPa]	2.37	2.37	2.37
	Compression perpendicular to the grain		stress	[MPa]	0.65	0.73	0.81
			strength	[MPa]	2.54	2.54	2.54
SLS	Deflection	Short term	deflection	[mm]	9.88	9.98	9.91
			limit	[mm]	10	10	10
		Long term	deflection	[mm]	13.3	13.4	13.3
			limit	[mm]	17.8	17.8	17.8
	Vibration	Vertical deflection	w/F	[mm/kN]	1.24	1.25	1.25
			a	[mm/kN]	1.5	1.5	1.5
		Unit impulse velocity response	ν	[m/Ns^2]	0.02	0.02	0.03
			$b^{(f1\zeta-1)}$	[m/Ns^2]	0.04	0.04	0.04

Table B. 4 – Design verifications of LVL product

Verifications				**units**	**LVL**
ULS	Bending		stress	[MPa]	11.8
			strength	[MPa]	31.1
	Shear		stress	[MPa]	0.59
			strength	[MPa]	2.89
	Compression perpendicular to the grain		stress	[MPa]	0.79
			strength	[MPa]	4.24
SLS	Deflection	Short term	deflection	[mm]	9.88
			limit	[mm]	10
		Long term	deflection	[mm]	13.3
			limit	[mm]	17.8
	Vibration	Vertical deflection	w/F	[mm/kN]	1.24
			a	[mm/kN]	1.5
		Unit impulse velocity response	ν	[m/Ns^2]	0.02
			$b^{(f1\zeta-1)}$	[m/Ns^2]	0.04

Table B. 5 – Design verifications of IJ products

		Verifications		**units**	**IJ (C24+OSB)**	**IJ (LVL+OSB)**
ULS	Bending	Tension in the middle of flange	stress	[MPa]	5.43	6.77
			strength	[MPa]	9.48	23.7
		Tension in the edge of flange	stress	[MPa]	7	8.73
			strength	[MPa]	16.3	32.5
		Tension in web	stress	[MPa]	2.4	2.38
			strength	[MPa]	4.54	4.54
		Shear	stress	[MPa]	4.63	4.63
			strength	[MPa]	12.8	12.8
SLS	Deflection	Short term	deflection	[mm]	9.99	9.94
			limit	[mm]	10	10
		Long term	deflection	[mm]	16.9	16.8
			limit	[mm]	17.8	17.8
	Vibration	Vertical deflection	w/F	[mm/kN]	0.95	0.93
			a	[mm/kN]	1.5	1.5
		Unit impulse velocity response	ν	[m/Ns^2]	0.02	0.02
			$b^{(f1\zeta-1)}$	[m/Ns^2]	0.03	0.03

Annex C – LCI of Cryptomeria, Scots pine and Spruce sawnwood production

Table C. 1 – Inputs and outputs of the “Sawnwood, softwood, raw {RoW}| sawing, softwood” process

Process	**Amount**	**unit**
Sawnwood, softwood, raw {RoW}| sawing, softwood	1.000	m^3
Input		
Lubricating oil {RoW}| market for lubricating oil | Cut-off, U	97.85	g
Pulpwood, softwood, measured as solid wood under bark {DE}| softwood forestry, pine, sustainable forest management	1.50	m3
Sawmill {GLO}| market for | Cut-off, U	0.00	p
Diesel, burned in building machine {GLO}| market for | Cut-off, U	26.90	MJ
Electricity, medium voltage | market for | Cut-off, U (Specific country)	18.00	kwh
Outputs		
Waste mineral oil {Europe without Switzerland}| market for waste mineral oil | Cut-off, U	14.63	kg

Table C. 2 - Inputs and outputs of the “Sawnwood, beam, softwood, raw, dried (u=10%) {RoW}| beam, softwood, raw, kiln drying to u=10%” process

Process	**Amount**	**unit**
Sawnwood, beam, softwood, raw, dried (u=10%) {RoW}| beam, softwood, raw, kiln drying to u=10%	1.00	m^3
Input		
Sawnwood, softwood, raw {RoW}| sawing, softwood | Cut-off, U	1.09	m^3
Technical wood drying facility {GLO}| market for | Cut-off, U	3.66E-06	p
Wood chips, wet, measured as dry mass {RoW}| wood chips production, softwood, at sawmill | Cut-off, U	61.37	kg
Electricity, medium voltage | market for | Cut-off, U (Specific country)	25.00	kwh
Furnace, wood chips, with silo, 300kW {GLO}| market for | Cut-off, U	8.95E-06	p
Outputs		
Wood ash mixture, pure {Europe without Switzerland}| market for wood ash mixture, pure | Cut-off, U	245.36	g
Emissões		
Acetaldehyde	3.14E-02	g
Ammonia	8.92E-01	g
Arsenic	5.15E-04	g
Benzene	4.69E-01	g
Benzene, ethyl-	1.55E-02	g
Benzene, hexachloro-	3.71E-09	g
Benzo(a)pyrene	2.58E-04	g
Bromine	3.09E-02	g
Cadmium	3.61E-04	g
Calcium	3.02E+00	g
Carbon dioxide, non-fossil	1.11E+05	g
Carbon monoxide, non-fossil	1.55E+02	g
Chlorine	9.28E-02	g
Chromium	2.04E-03	g

Chromium VI	2.06E-05	g
Copper	1.13E-02	g
Dinitrogen monoxide	1.19E+00	g
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	1.60E-08	g
Fluorine	2.58E-02	g
Formaldehyde	6.70E-02	g
Hydrocarbons, aliphatic, alkanes, unspecified	4.69E-01	g
Hydrocarbons, aliphatic, unsaturated	1.60E+00	g
Lead	1.29E-02	g
Magnesium	1.86E-01	g
Manganese	8.76E-02	g
Mercury	1.55E-04	g
Methane, non-fossil	2.06E-01	g
NMVOC, non-methane volatile organic compounds, unspecified origin	1.20E+01	g
Nickel	3.09E-03	g
Nitrogen oxides	9.28E+01	g
PAH, polycyclic aromatic hydrocarbons	5.72E-03	g
Particulates, < 2.5 um	1.03E+02	g
Particulates, > 2.5 um, and < 10um	2.58E+00	g
Phenol, pentachloro-	4.18E-06	g
Phosphorus	1.55E-01	g
Potassium	1.21E+01	g
Sodium	6.70E-01	g
Sulfur dioxide	1.29E+00	g
Toluene	1.55E-01	g
Water	2.52E+02	g
Zinc	1.55E-01	g
m-Xylene	6.19E-02	g

Table C. 3 - Inputs and outputs of the “Sawnwood, beam, softwood, dried (u=10%), planed {RoW}| planing, beam, softwood, u=10%” process

Process	**Amount**	**unit**
Sawnwood, beam, softwood, dried (u=10%), planed {RoW}| planing, beam, softwood, u=10%	1.000	m^3
Input		
Planing mill {GLO}| market for | Cut-off, U	6.95E-07	p
Sawnwood, beam, softwood, raw, dried (u=10%) {RoW}| beam, softwood, raw, kiln drying to u=10%	1.04E+00	m^3
Electricity, medium voltage | market for | Cut-off, U (Specific country)	8.66E+00	kwh

Annex D – LCI of Eucalyptus sawnwood production

Table D. 1 - Inputs and outputs of the “Sawnwood, Hardwood, raw {RoW}| sawing, hardwood | Cut-off, U” process

Process	**Amount**	**unit**
Sawnwood, Hardwood, raw {RoW}| sawing, hardwood | Cut-off, U	1.000	m^3
Input		
Lubricating oil {RoW}| market for lubricating oil | Cut-off, U	97.30	g
Pulpwood, softwood, measured as solid wood under bark {DE}| softwood forestry, pine, sustainable forest management	1.49	m^3
Sawmill {GLO}| market for | Cut-off, U	0.00	p
Diesel, burned in building machine {GLO}| market for | Cut-off, U	26.70	MJ
Electricity, medium voltage | market for | Cut-off, U (Specific country)	19.40	kwh
Outputs		
Waste mineral oil {Europe without Switzerland}| market for waste mineral oil | Cut-off, U	14.50	kg

Table D. 2 - Inputs and outputs of the “Sawnwood, beam, softwood, raw, dried (u=10%) {RoW}| beam, softwood, raw, kiln drying to u=10%” process

Process	**Amount**	**unit**
Sawnwood, beam, softwood, raw, dried (u=10%) {RoW}| beam, softwood, raw, kiln drying to u=10%	1.00	m^3
Input		
Sawnwood, softwood, raw {RoW}| sawing, softwood | Cut-off, U	1.09	m^3
Technical wood drying facility {GLO}| market for | Cut-off, U	3.66E-06	p
Wood chips, wet, measured as dry mass {RoW}| wood chips production, softwood, at sawmill | Cut-off, U	96.40	kg
Electricity, medium voltage | market for | Cut-off, U (Specific country)	35.00	kwh
Furnace, wood chips, with silo, 300kW {GLO}| market for | Cut-off, U	2.57E-05	p
Outputs		
Wood ash mixture, pure {Europe without Switzerland}| market for wood ash mixture, pure | Cut-off, U	741.00	g
Emissions		
Acetaldehyde	9.04E-02	g
Ammonia	2.56E+00	g
Arsenic	1.48E-03	g
Benzene	1.35E+00	g
Benzene, ethyl-	4.44E-02	g
Benzene, hexachloro-	1.07E-08	g
Benzo(a)pyrene	7.41E-04	g
Bromine	8.89E-02	g
Cadmium	1.04E-03	g
Calcium	8.67E+00	g
Carbon dioxide, non-fossil	1.75E+05	g
Carbon monoxide, non-fossil	3.70E+02	g
Chlorine	2.67E-01	g

Chromium	5.87E-03	g
Chromium VI	5.93E-05	g
Copper	3.26E-02	g
Dinitrogen monoxide	3.41E+00	g
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	4.59E-08	g
Fluorine	7.41E-02	g
Formaldehyde	1.93E-01	g
Hydrocarbons, aliphatic, alkanes, unspecified	1.35E+00	g
Hydrocarbons, aliphatic, unsaturated	4.59E+00	g
Lead	3.70E-02	g
Magnesium	5.33E-01	g
Manganese	2.52E-01	g
Mercury	4.44E-04	g
Methane, non-fossil	3.56E+00	g
NMVOC, non-methane volatile organic compounds, unspecified origin	1.76E+01	g
Nickel	8.89E-03	g
Nitrogen oxides	2.67E+02	g
PAH, polycyclic aromatic hydrocarbons	1.64E-02	g
Particulates, < 2.5 um	1.51E+02	g
Particulates, > 2.5 um, and < 10um	8.40E+00	g
Phenol, pentachloro-	1.20E-05	g
Phosphorus	4.44E-01	g
Potassium	3.47E+01	g
Sodium	1.93E+00	g
Sulfur dioxide	3.70E+00	g
Toluene	4.44E-01	g
Water	3.67E+02	g
Zinc	4.44E-01	g
m-Xylene	1.78E-01	g

Table D-3 - Inputs and outputs of the “Sawnwood, beam, softwood, dried (u=10%), planed {RoW}| planing, beam, softwood, u=10% | Cut-off, U” process

Process	**Amount**	**unit**
Sawnwood, beam, softwood, dried (u=10%), planed {RoW}| planing, beam, softwood, u=10% | Cut-off, U	1.000	m^3
Input		
Planing mill {GLO}| market for | Cut-off, U	6.97E-07	p
Sawnwood, beam, softwood, raw, dried (u=10%) {RoW}| beam, softwood, raw, kiln drying to u=10% | Cut-off, U	1.05E+00	m^3
Electricity, medium voltage | market for | Cut-off, U (Specific country)	8.68E+00	kwh

Annex E – Environmental impacts of forest management scenarios

Table E. 1 - Environmental impacts of roundwood scenarios (Stage A1) – per cubic meter

Category	**Unit**	**Crypt_Plant_PT**	**Euc_Plant_PT**	**MP_NR_PT**	**MP_Plant_PT**	**MP_Seed_PT**	**SPine_Plant_DE**	**SPine_Plant_SE**	**Spruce_Plant_DE**	**Spruce_Plant_SE**
GWP-t	kg CO2 eq	-5.45E+02	-1.37E+03	-9.25E+02	-9.24E+02	-9.23E+02	-8.74E+02	-8.77E+02	-7.67E+02	-7.70E+02
GWP-f	kg CO2 eq	8.28E+00	1.76E+01	1.06E+01	1.16E+01	1.12E+01	1.13E+01	9.66E+00	1.01E+01	8.42E+00
GWP-b	kg CO2 eq	-5.53E+02	-1.39E+03	-9.36E+02	-9.36E+02	-9.35E+02	-8.87E+02	-8.87E+02	-7.78E+02	-7.79E+02
GWP-lu-luc	kg CO2 eq	1.57E-01	1.63E-01	1.98E-01	2.01E-01	1.98E-01	8.92E-01	3.19E-01	9.09E-01	2.26E-01
ODP	kg CFC11 eq	1.91E-06	2.99E-06	1.94E-06	2.08E-06	2.01E-06	2.33E-06	2.08E-06	2.16E-06	1.87E-06
AP	mol H+ eq	4.36E-02	9.92E-02	5.49E-02	6.76E-02	6.47E-02	6.00E-02	5.49E-02	5.02E-02	4.64E-02
EP-f	kg P eq	9.49E-04	1.27E-03	1.21E-03	1.61E-03	1.58E-03	5.45E-03	1.97E-03	5.52E-03	1.39E-03
EP-m	kg N eq	1.75E-02	3.04E-02	1.82E-02	2.09E-02	1.99E-02	2.49E-02	2.18E-02	2.15E-02	1.85E-02
EP-t	mol N eq	1.85E-01	3.75E-01	2.15E-01	2.45E-01	2.33E-01	2.29E-01	2.25E-01	1.91E-01	1.93E-01
POCP	kg NMVOC eq	7.30E-02	9.99E-02	8.41E-02	9.21E-02	8.89E-02	2.65E-01	1.10E-01	2.59E-01	7.94E-02
ADP-f	MJ	1.18E+02	1.99E+02	1.25E+02	1.40E+02	1.35E+02	1.57E+02	1.37E+02	1.40E+02	1.20E+02
ADP-m	kg Sb eq	7.44E-06	1.57E-04	2.24E-05	2.00E-04	1.97E-04	2.32E-05	1.20E-05	2.19E-05	9.54E-06
WDP	m3 depriv.	4.88E-01	3.10E+00	1.63E+00	2.45E+00	2.39E+00	4.42E+00	1.25E+00	3.86E+00	8.70E-01
PM	disease inc.	1.56E-07	5.16E-07	2.43E-07	3.41E-07	3.32E-07	6.29E-07	5.69E-07	4.55E-07	4.19E-07
IRP	kBq U-235 eq	5.15E-01	8.09E-01	5.15E-01	5.89E-01	5.59E-01	7.35E-01	6.17E-01	6.35E-01	5.34E-01
ETP-fw	CTUe	5.04E+01	1.97E+02	1.12E+02	1.26E+02	1.23E+02	1.22E+02	7.56E+01	1.14E+02	5.95E+01
HTP-c	CTUh	1.32E-07	1.25E-07	1.47E-07	1.81E-07	1.72E-07	5.66E-07	1.86E-07	5.69E-07	1.17E-07
HTP-nc	CTUh	2.85E-09	3.07E-09	4.10E-09	5.09E-09	4.98E-09	2.17E-08	5.61E-09	2.20E-08	3.24E-09
SQP	Pt	1.29E+04	1.45E+04	2.17E+04	2.17E+04	2.14E+04	5.61E+04	6.44E+04	3.68E+04	5.06E+04

Annex F – Environmental impacts of production of construction products

Table F. 1 - Environmental impacts of production of construction products (Stages A1-A3) – per cubic meter

Category	**Unit**	**GLT**	**LVL**	**SW_Crypt_PT**	**SW_Euc_PT**	**SW_MP_PT**	**SW_Pine_DE**	**SW_Pine_SE**	**SW_Spruce_DE**	**SW_Spruce_SE**
GWP-t	kg CO2 eq	-5.61E+02	-5.63E+02	-4.94E+02	-1.50E+03	-9.58E+02	-7.87E+02	-8.15E+02	-6.78E+02	-7.13E+02
GWP-f	kg CO2 eq	1.63E+02	3.15E+02	3.94E+01	6.11E+01	7.15E+01	5.76E+01	3.08E+01	6.27E+01	2.87E+01
GWP-b	kg CO2 eq	-7.25E+02	-8.81E+02	-5.34E+02	-1.56E+03	-1.03E+03	-8.46E+02	-8.46E+02	-7.43E+02	-7.43E+02
GWP-lu-luc	kg CO2 eq	9.34E-01	2.52E+00	5.68E-01	6.70E-01	1.11E+00	1.57E+00	7.27E-01	1.60E+00	5.68E-01
ODP	kg CFC11 eq	2.40E-05	4.85E-05	5.10E-06	7.25E-06	1.12E-05	6.03E-06	7.27E-06	7.38E-06	6.91E-06
AP	mol H+ eq	1.31E+00	2.57E+00	3.56E-01	6.34E-01	4.61E-01	3.01E-01	2.56E-01	3.22E-01	2.42E-01
EP-f	kg P eq	1.19E-02	2.76E-02	2.76E-03	3.79E-03	6.22E-03	1.46E-02	3.67E-03	1.47E-02	2.67E-03
EP-m	kg N eq	4.04E-01	6.67E-01	1.04E-01	2.03E-01	1.36E-01	1.09E-01	1.07E-01	1.18E-01	1.02E-01
EP-t	mol N eq	4.78E+00	9.00E+00	1.15E+00	2.33E+00	1.56E+00	1.20E+00	1.17E+00	1.30E+00	1.11E+00
POCP	kg NMVOC eq	1.35E+00	2.59E+00	3.49E-01	6.08E-01	5.44E-01	6.49E-01	3.95E-01	6.82E-01	3.43E-01
ADP-f	MJ	2.75E+03	5.95E+03	5.24E+02	7.28E+02	8.93E+02	7.91E+02	7.09E+02	8.62E+02	6.80E+02
ADP-m	kg Sb eq	1.51E-04	3.17E-04	2.33E-05	2.78E-04	1.12E-04	1.16E-04	3.45E-05	1.14E-04	3.04E-05
WDP	m3 depriv.	6.99E+01	3.39E+02	1.21E+01	1.91E+01	1.84E+01	8.78E+00	6.17E+00	7.80E+00	5.52E+00
PM	disease inc.	7.61E-05	1.78E-04	2.72E-05	4.04E-05	3.40E-06	2.80E-05	2.83E-05	2.83E-05	2.81E-05
IRP	kBq U-235 eq	1.62E+01	2.93E+01	1.70E+00	2.37E+00	3.20E+00	2.98E+00	1.25E+01	3.25E+00	1.23E+01
ETP-fw	CTUe	5.86E+03	1.35E+04	9.10E+02	2.42E+03	6.89E+02	1.04E+03	8.96E+02	1.06E+03	8.69E+02
HTP-c	CTUh	4.74E-06	1.11E-05	7.57E-07	1.40E-06	8.15E-07	1.56E-06	8.12E-07	1.64E-06	6.93E-07
HTP-nc	CTUh	5.26E-07	2.70E-06	1.36E-08	2.63E-08	2.08E-08	4.66E-08	1.83E-08	4.85E-08	1.42E-08
SQP	Pt	1.43E+05	1.34E+05	2.39E+04	2.74E+04	9.78E+04	9.74E+04	1.12E+05	6.45E+04	8.82E+04

Annex G – Environmental impacts of building solutions

Table G. 1 - Environmental impacts of building solutions (Stages A1-A5) – per structural solution

Category	Unit	GLT	LVL	SW_Euc_PT	SW_MP_PT	SW_Pine_DE	SW_Pine_SE	SW_Spruce_DE	SW_Spruce_SE	IJ C24	IJ LVL
GWP-t	kg CO2 eq	-8.25E+01	8.95E+01	-4.94E+02	-3.13E+02	-1.63E+02	-1.35E+02	-1.15E+02	-9.71E+01	-4.26E+01	5.26E+01
GWP-f	kg CO2 eq	2.93E+02	3.84E+02	2.25E+02	1.99E+02	2.93E+02	3.21E+02	2.84E+02	3.03E+02	2.61E+02	3.48E+02
GWP-b	kg CO2 eq	-3.76E+02	-2.96E+02	-7.20E+02	-5.12E+02	-4.57E+02	-4.57E+02	-4.01E+02	-4.01E+02	-3.04E+02	-2.96E+02
GWP-luluc	kg CO2 eq	8.94E-01	1.50E+00	7.18E-01	5.09E-01	1.26E+00	8.03E-01	1.27E+00	7.17E-01	6.80E-01	1.31E+00
ODP	kg CFC11 eq	5.52E-05	7.32E-05	4.35E-05	4.47E-05	5.86E-05	6.93E-05	5.67E-05	6.52E-05	4.87E-05	6.32E-05
AP	mol H+ eq	2.10E+00	2.80E+00	1.61E+00	1.52E+00	1.94E+00	2.21E+00	1.88E+00	2.09E+00	1.77E+00	2.47E+00
EP-f	kg P eq	1.23E-02	1.81E-02	7.91E-03	9.25E-03	1.41E-02	8.21E-03	1.41E-02	7.66E-03	1.00E-02	1.74E-02
EP-m	kg N eq	7.36E-01	9.29E-01	5.73E-01	5.38E-01	7.35E-01	8.55E-01	7.08E-01	8.05E-01	6.23E-01	7.97E-01
EP-t	mol N eq	7.93E+00	1.06E+01	6.02E+00	5.62E+00	7.75E+00	9.06E+00	7.44E+00	8.51E+00	6.48E+00	8.94E+00
POCP	kg NMVOC eq	2.37E+00	3.11E+00	1.82E+00	1.78E+00	2.44E+00	2.65E+00	2.37E+00	2.49E+00	2.00E+00	2.69E+00
ADP-f	MJ	4.95E+03	6.68E+03	3.71E+03	3.75E+03	4.73E+03	5.29E+03	4.60E+03	5.04E+03	4.39E+03	6.13E+03
ADP-m	kg Sb eq	2.23E-04	2.85E-04	2.73E-04	2.00E-04	2.11E-04	1.69E-04	2.09E-04	1.66E-04	3.49E-04	4.32E-04
WDP	m3 depriv.	8.58E+01	1.96E+02	5.83E+01	5.87E+01	5.41E+01	5.25E+01	5.36E+01	5.22E+01	6.32E+01	1.74E+02
PM	disease inc.	5.62E-05	9.80E-05	3.38E-05	1.65E-05	3.74E-05	4.20E-05	3.64E-05	4.01E-05	2.91E-05	7.86E-05
IRP	kBq U-235 eq	2.23E+01	2.91E+01	1.43E+01	1.45E+01	1.89E+01	2.67E+01	1.83E+01	2.56E+01	1.80E+01	2.68E+01
ETP-fw	CTUe	8.61E+03	1.16E+04	6.62E+03	5.82E+03	6.44E+03	6.61E+03	6.39E+03	6.50E+03	6.94E+03	1.10E+04
HTP-c	CTUh	1.20E-05	1.48E-05	1.00E-05	9.70E-06	1.11E-05	1.12E-05	1.10E-05	1.09E-05	1.09E-05	1.43E-05
HTP-nc	CTUh	1.33E-06	2.24E-06	1.06E-06	1.06E-06	1.10E-06	1.10E-06	1.10E-06	1.09E-06	1.18E-06	2.07E-06
SQP	Pt	1.15E+05	9.92E+04	5.39E+04	8.98E+04	9.38E+04	1.02E+05	7.61E+04	8.89E+04	9.16E+04	9.02E+04

Table G. 2 - Environmental impacts of incineration of building solutions (Stages C1-C4) – per structural solution

Category	**Unit**	**GLT**	**LVL**	**SW_Euc_PT**	**SW_MP_PT**	**SW_Pine_DE**	**SW_Pine_SE**	**SW_Spruce_DE**	**SW_Spruce_SE**	**IJ C24**	**IJ LVL**
GWP-t	kg CO2 eq	4.02E+02	3.22E+02	7.54E+02	5.40E+02	4.83E+02	4.83E+02	4.26E+02	4.26E+02	3.28E+02	3.19E+02
GWP-f	kg CO2 eq	2.57E+01	2.59E+01	3.41E+01	2.80E+01	2.64E+01	2.64E+01	2.47E+01	2.47E+01	2.41E+01	2.29E+01
GWP-b	kg CO2 eq	3.76E+02	2.96E+02	7.20E+02	5.12E+02	4.57E+02	4.57E+02	4.01E+02	4.01E+02	3.04E+02	2.96E+02
GWP-lu-luc	kg CO2 eq	6.15E-05	6.18E-05	8.95E-05	7.26E-05	6.81E-05	6.81E-05	6.35E-05	6.35E-05	4.75E-05	4.75E-05
ODP	kg CFC11 eq	2.78E-06	2.80E-06	3.99E-06	3.24E-06	3.04E-06	3.04E-06	2.84E-06	2.84E-06	2.38E-06	2.31E-06
AP	mol H+ eq	4.48E-01	4.51E-01	4.09E-01	3.56E-01	3.42E-01	3.42E-01	3.28E-01	3.28E-01	4.41E-01	4.14E-01
EP-f	kg P eq	1.22E-05	1.22E-05	1.54E-05	1.27E-05	1.20E-05	1.20E-05	1.13E-05	1.13E-05	1.12E-05	1.07E-05
EP-m	kg N eq	1.93E-01	1.94E-01	1.53E-01	1.37E-01	1.32E-01	1.32E-01	1.28E-01	1.28E-01	1.90E-01	1.78E-01
EP-t	mol N eq	2.25E+00	2.26E+00	1.88E+00	1.66E+00	1.61E+00	1.61E+00	1.55E+00	1.55E+00	2.21E+00	2.08E+00
POCP	kg NMVOC eq	5.00E-01	5.03E-01	4.02E-01	3.59E-01	3.47E-01	3.47E-01	3.35E-01	3.35E-01	4.91E-01	4.60E-01
ADP-f	MJ	3.98E+02	4.00E+02	5.31E+02	4.35E+02	4.10E+02	4.10E+02	3.84E+02	3.84E+02	3.75E+02	3.56E+02
ADP-m	kg Sb eq	2.92E-05	2.94E-05	4.46E-05	3.60E-05	3.37E-05	3.37E-05	3.13E-05	3.13E-05	2.94E-05	2.74E-05
WDP	m3 depriv.	8.02E+01	8.07E+01	1.15E+02	9.37E+01	8.80E+01	8.80E+01	8.21E+01	8.21E+01	8.10E+01	7.55E+01
PM	disease inc.	2.03E-06	2.04E-06	2.40E-06	2.00E-06	1.90E-06	1.90E-06	1.79E-06	1.79E-06	1.88E-06	1.79E-06
IRP	kBq U-235 eq	2.03E+00	2.04E+00	2.86E+00	2.33E+00	2.19E+00	2.19E+00	2.05E+00	2.05E+00	1.93E+00	1.83E+00
ETP-fw	CTUe	1.00E+02	1.01E+02	1.38E+02	1.13E+02	1.06E+02	1.06E+02	9.93E+01	9.93E+01	9.12E+01	8.72E+01
HTP-c	CTUh	8.30E-07	8.35E-07	1.25E-06	1.01E-06	9.43E-07	9.43E-07	8.79E-07	8.79E-07	8.17E-07	7.67E-07
HTP-nc	CTUh	1.23E-08	1.24E-08	1.81E-08	1.46E-08	1.37E-08	1.37E-08	1.28E-08	1.28E-08	1.18E-08	1.11E-08
SQP	Pt	2.73E-01	2.74E-01	3.97E-01	3.22E-01	3.02E-01	3.02E-01	2.82E-01	2.82E-01	2.11E-01	2.11E-01

Table G. 3 - Environmental impacts of incineration of landfilling solutions (Stages C1-C4) – per structural solution

Category	**Unit**	**GLT**	**LVL**	**SW_Euc_PT**	**SW_MP_PT**	**SW_Pine_DE**	**SW_Pine_SE**	**SW_Spruce_DE**	**SW_Spruce_SE**	**IJ C24**	**IJ LVL**
GWP-t	kg CO2 eq	1.42E+02	1.72E+02	3.06E+02	2.02E+02	1.66E+02	1.66E+02	1.46E+02	1.46E+02	1.46E+02	1.74E+02
GWP-f	kg CO2 eq	1.41E+02	1.72E+02	3.05E+02	2.01E+02	1.65E+02	1.65E+02	1.45E+02	1.45E+02	1.45E+02	1.73E+02
GWP-b	kg CO2 eq	6.87E-01	6.91E-01	1.00E+00	8.11E-01	7.60E-01	7.60E-01	7.09E-01	7.09E-01	6.92E-01	6.46E-01
GWP-lu-luc	kg CO2 eq	6.15E-05	6.18E-05	8.95E-05	7.26E-05	6.81E-05	6.81E-05	6.35E-05	6.35E-05	4.75E-05	4.75E-05
ODP	kg CFC11 eq	2.79E-06	2.81E-06	4.07E-06	3.30E-06	3.09E-06	3.09E-06	2.89E-06	2.89E-06	2.39E-06	2.33E-06
AP	mol H+ eq	3.14E-01	3.16E-01	4.54E-01	3.69E-01	3.46E-01	3.46E-01	3.23E-01	3.23E-01	3.05E-01	2.87E-01
EP-f	kg P eq	3.34E-03	3.36E-03	5.05E-03	4.08E-03	3.82E-03	3.82E-03	3.56E-03	3.56E-03	3.37E-03	3.14E-03
EP-m	kg N eq	4.41E-01	4.44E-01	3.48E-01	3.11E-01	3.02E-01	3.02E-01	2.92E-01	2.92E-01	4.40E-01	4.12E-01
EP-t	mol N eq	1.24E+00	1.25E+00	1.79E+00	1.46E+00	1.37E+00	1.37E+00	1.28E+00	1.28E+00	1.20E+00	1.13E+00
POCP	kg NMVOC eq	3.27E-01	3.29E-01	4.72E-01	3.83E-01	3.60E-01	3.60E-01	3.36E-01	3.36E-01	3.16E-01	2.98E-01
ADP-f	MJ	5.99E+02	6.03E+02	8.72E+02	7.07E+02	6.63E+02	6.63E+02	6.19E+02	6.19E+02	5.79E+02	5.45E+02
ADP-m	kg Sb eq	2.85E-06	2.87E-06	4.15E-06	3.37E-06	3.16E-06	3.16E-06	2.95E-06	2.95E-06	2.77E-06	2.61E-06
WDP	m3 depriv.	7.43E+00	7.48E+00	1.07E+01	8.71E+00	8.17E+00	8.17E+00	7.63E+00	7.63E+00	7.51E+00	7.00E+00
PM	disease inc.	1.83E-06	1.84E-06	2.66E-06	2.16E-06	2.02E-06	2.02E-06	1.89E-06	1.89E-06	1.69E-06	1.61E-06
IRP	kBq U-235 eq	2.05E+00	2.07E+00	2.99E+00	2.42E+00	2.27E+00	2.27E+00	2.12E+00	2.12E+00	1.96E+00	1.85E+00
ETP-fw	CTUe	1.17E+03	1.17E+03	7.63E+02	7.12E+02	6.98E+02	6.98E+02	6.85E+02	6.85E+02	1.17E+03	1.09E+03
HTP-c	CTUh	1.37E-07	1.38E-07	1.98E-07	1.61E-07	1.51E-07	1.51E-07	1.41E-07	1.41E-07	1.18E-07	1.15E-07
HTP-nc	CTUh	7.86E-09	7.91E-09	1.14E-08	9.23E-09	8.66E-09	8.66E-09	8.09E-09	8.09E-09	7.34E-09	6.98E-09
SQP	Pt	2.73E-01	2.74E-01	3.97E-01	3.22E-01	3.02E-01	3.02E-01	2.82E-01	2.82E-01	2.11E-01	2.11E-01

Annex H – Environmental impacts of deck solutions

Table H. 1 - Environmental impacts of life cycle operations of PT and ST preservative products – per kg of product

Category	Unit	Total	PT production	PT application	PT use	PT end-of-life	ST production	ST application	ST use	ST end-of-life
GWP-t	kg CO2 eq	7.82E+01	1.57E+00	3.38E-01	0.00E+00	1.47E+00	6.58E+00	0.00E+00	0.00E+00	1.47E+00
GWP-f	kg CO2 eq	7.76E+01	1.55E+00	3.34E-01	0.00E+00	1.06E-02	6.50E+00	0.00E+00	0.00E+00	1.03E-02
GWP-b	kg CO2 eq	0.00E+00	1.21E-02	3.14E-03	0.00E+00	1.46E+00	7.92E-02	0.00E+00	0.00E+00	1.46E+00
GWP-luluc	kg CO2 eq	6.97E-01	1.08E-03	6.07E-04	0.00E+00	9.03E-07	1.11E-03	0.00E+00	0.00E+00	7.73E-07
ODP	kg CFC11 eq	8.95E-06	9.73E-08	2.22E-08	0.00E+00	7.84E-10	1.22E-06	0.00E+00	0.00E+00	7.49E-10
AP	mol H+ eq	1.49E+00	6.89E-02	1.85E-03	0.00E+00	1.47E-04	1.87E-02	0.00E+00	0.00E+00	1.45E-04
EP-f	kg P eq	1.30E-02	5.48E-04	1.85E-05	0.00E+00	5.95E-08	1.87E-04	0.00E+00	0.00E+00	5.39E-08
EP-m	kg N eq	1.96E-01	5.08E-03	2.82E-04	0.00E+00	7.33E-05	2.50E-03	0.00E+00	0.00E+00	7.31E-05
EP-t	mol N eq	2.15E+00	5.37E-02	3.15E-03	0.00E+00	7.79E-04	2.76E-02	0.00E+00	0.00E+00	7.76E-04
POCP	kg NMVOC eq	6.45E-01	1.45E-02	8.55E-04	0.00E+00	1.86E-04	1.41E-02	0.00E+00	0.00E+00	1.85E-04
ADP-f	MJ	1.05E+03	2.54E+01	4.38E+00	0.00E+00	8.36E-02	7.22E+01	0.00E+00	0.00E+00	8.17E-02
ADP-m	kg Sb eq	6.28E-03	3.67E-04	1.09E-05	0.00E+00	9.27E-08	1.72E-05	0.00E+00	0.00E+00	7.30E-08
WDP	m3 depriv.	5.03E+01	9.68E-01	1.15E+00	0.00E+00	1.27E-02	7.32E-01	0.00E+00	0.00E+00	1.29E-02
PM	disease inc.	5.53E-06	1.70E-07	1.29E-08	0.00E+00	1.39E-09	2.02E-07	0.00E+00	0.00E+00	1.38E-09
IRP	kBq U-235 eq	2.98E+00	4.31E-02	1.99E-02	0.00E+00	8.07E-05	2.61E-01	0.00E+00	0.00E+00	7.35E-05
ETP-fw	CTUe	1.51E+04	6.40E+02	7.30E+00	2.47E+02	1.62E-01	1.68E+02	6.58E-01	4.58E-01	1.20E-01
HTP-c	CTUh	1.37E-05	7.55E-07	2.93E-09	2.69E-09	2.03E-09	1.69E-07	1.07E-11	2.77E-11	2.01E-09
HTP-nc	CTUh	1.24E-06	1.11E-08	6.38E-11	0.00E+00	2.91E-09	3.78E-09	0.00E+00	0.00E+00	2.59E-11
SQP	Pt	5.88E+04	6.20E+00	4.34E-01	0.00E+00	6.13E-03	5.51E+00	0.00E+00	0.00E+00	4.87E-03

Annex I - Environmental impacts of roundwood scenarios calculated with other LCIA methodologies

Table I. 1 - Environmental impacts of roundwood scenarios calculated with CML 2001 methodology – per m3 of product

Category	Unit	MP_Seed_PT	MP_Plant_PT	MP_NR_PT	Euc_Plant_PT
ADP	kg Sb	6.49E-02	6.73E-02	5.92E-02	9.54E-02
GWP	kg CO_2	1.13E+01	1.17E+01	1.07E+01	1.76E+01
POFP	kg C_2H_4	7.39E-03	7.52E-03	7.18E-03	4.28E-03
AP	kg SO_2	4.81E-02	5.02E-02	3.99E-02	7.24E-02
EP	kg PO_{34}	1.43E-02	1.47E-02	1.23E-02	1.76E-02

Table I. 2 - Environmental impacts of the roundwood scenarios calculated with the CML-IA (baseline) V3.05/World 2000 methodology – per m3 of product

Category	Unit	MP_Seed_PT	MP_Plant_PT	MP_NR_PT
ADP-m	kg Sb eq	1.97E-04	2.00E-04	2.24E-05
ADP-f	MJ	1.33E+02	1.38E+02	1.24E+02
GWP	kg CO2 eq	1.10E+01	1.14E+01	1.04E+01
ODP	kg CFC-11 eq	1.60E-06	1.66E-06	1.54E-06
Human toxicity	kg 1,4-DB eq	1.05E+00	1.09E+00	8.44E-01
Freshwater aquatic ecotox	kg 1,4-DB eq	2.25E-01	2.29E-01	1.89E-01
Marine aquatic ecotox	kg 1,4-DB eq	2.18E+03	2.27E+03	5.32E+02
Terrestrial ecotox	kg 1,4-DB eq	5.64E-02	5.73E-02	5.40E-02
Photochemical ecotox	kg C2H4 eq	7.39E-03	7.52E-03	7.18E-03
Acidification	kg SO2 eq	4.81E-02	5.02E-02	3.99E-02
Eutrophication	kg PO4--- eq	1.59E-02	1.64E-02	1.39E-02

Annex J – Environmental impacts of roundwood scenarios calculated by an economic allocation

Table J. 1 - Environmental impacts of the roundwood scenarios calculated by an economic allocation – per m3 of product

Category	Unit	Crypt_Plant_PT	Euc_Plant_PT	MP_NR_PT	MP_Plant_PT	MP_Seed_PT
GWP-t	kg CO2 eq	-6.29E+02	-1.41E+03	-1.03E+03	-1.02E+03	-1.04E+03
GWP-f	kg CO2 eq	9.57E+00	1.81E+01	1.17E+01	1.29E+01	1.26E+01
GWP-b	kg CO2 eq	-6.39E+02	-1.43E+03	-1.04E+03	-1.04E+03	-1.05E+03
GWP-luluc	kg CO2 eq	1.81E-01	1.69E-01	2.19E-01	2.23E-01	2.22E-01
ODP	kg CFC11 eq	2.21E-06	3.09E-06	2.15E-06	2.30E-06	2.26E-06
AP	mol H+ eq	5.04E-02	1.02E-01	6.09E-02	7.49E-02	7.26E-02
EP-f	kg P eq	1.10E-03	1.31E-03	1.34E-03	1.78E-03	1.77E-03
EP-m	kg N eq	2.02E-02	3.13E-02	2.02E-02	2.32E-02	2.23E-02
EP-t	mol N eq	2.13E-01	3.87E-01	2.38E-01	2.71E-01	2.62E-01
POCP	kg NMVOC eq	8.44E-02	1.03E-01	9.32E-02	1.02E-01	9.97E-02
ADP-f	MJ	1.36E+02	2.05E+02	1.38E+02	1.55E+02	1.51E+02
ADP-m	kg Sb eq	8.60E-06	1.62E-04	2.48E-05	2.21E-04	2.21E-04
WDP	m3 depriv.	5.64E-01	3.20E+00	1.81E+00	2.72E+00	2.68E+00
PM	disease inc.	1.81E-07	5.33E-07	2.69E-07	3.79E-07	3.73E-07
IRP	kBq U-235 eq	5.95E-01	8.35E-01	5.71E-01	6.53E-01	6.27E-01
ETP-fw	CTUe	5.83E+01	2.04E+02	1.24E+02	1.40E+02	1.38E+02
HTP-nc	CTUh	1.52E-07	1.29E-07	1.63E-07	2.01E-07	1.92E-07
HTP-c	CTUh	3.30E-09	3.17E-09	4.54E-09	5.64E-09	5.59E-09
SQP	Pt	1.49E+04	1.50E+04	2.40E+04	2.41E+04	2.41E+04

Annex K - Environmental impacts of roundwood scenarios calculated by NDB LCI methodology

Table K. 1 - Environmental impacts of the roundwood scenarios calculated by the NDB LCI methodology – per m3 of product

Category	**Unit**	**Crypt_Plant_PT_NDB**	**Euc_Plant_PT_NDB**	**MP_NR_PT_NDB**	**MP_Plant_PT_NDB**	**MP_Seed_PT_NDB**
GWP-t	kg CO2 eq	-5.46E+02	-1.37E+03	-9.27E+02	-9.25E+02	-9.25E+02
GWP-f	kg CO2 eq	7.32E+00	1.56E+01	9.42E+00	1.08E+01	1.05E+01
GWP-b	kg CO2 eq	-5.53E+02	-1.39E+03	-9.36E+02	-9.36E+02	-9.35E+02
GWP-luluc	kg CO2 eq	1.71E-04	3.04E-03	6.45E-04	3.57E-03	3.33E-03
ODP	kg CFC11 eq	1.69E-06	2.55E-06	1.67E-06	1.89E-06	1.84E-06
AP	mol H+ eq	7.77E-02	1.40E-01	8.52E-02	1.02E-01	9.89E-02
EP-f	kg P eq	8.74E-06	3.06E-04	2.32E-05	4.22E-04	4.08E-04
EP-m	kg N eq	3.46E-02	5.12E-02	3.33E-02	3.76E-02	3.67E-02
EP-t	mol N eq	3.79E-01	6.12E-01	3.90E-01	4.38E-01	4.27E-01
POCP	kg NMVOC eq	1.07E-01	1.56E-01	1.03E-01	1.17E-01	1.14E-01
ADP-f	MJ	1.05E+02	1.73E+02	1.09E+02	1.30E+02	1.25E+02
ADP-m	kg Sb eq	9.41E-06	1.60E-04	2.30E-05	2.01E-04	1.99E-04
WDP	m3 depriv.	5.02E-02	2.65E+00	1.06E+00	1.89E+00	1.83E+00
PM	disease inc.	2.06E-06	3.00E-06	1.93E-06	2.23E-06	2.18E-06
IRP	kBq U-235 eq	4.57E-01	6.92E-01	4.44E-01	5.41E-01	5.13E-01
ETP-fw	CTUe	3.57E+01	1.78E+02	9.30E+01	1.09E+02	1.07E+02
HTP-nc	CTUh	7.10E-08	8.80E-08	9.17E-08	1.09E-07	1.07E-07
HTP-c	CTUh	5.28E-10	1.77E-09	7.69E-10	1.73E-09	1.69E-09
SQP	Pt	1.29E+04	1.45E+04	2.17E+04	2.17E+04	2.14E+04

Annex L – Environmental impacts of SW, GLT and LVL scenarios calculated with CML 2001 methodology

Table L. 1 - Environmental impacts of the SW, GLT and LVL scenarios calculated with the CML 2001 v 2.05 and West Europe – 1995 methodology

Cate-gory	**Unit**	**SW_Spruce_SE**	**SW_SPruce_DE**	**SW_Pine_SE**	**SW_PINE_DE**	**SW_MP_PT**	**SW_Euc_PT**	**SW_Crypt_PT**	**GLT**	**LVL**
AP	kg SO2 eq	2.19E-01	2.82E-01	2.31E-01	2.63E-01	3.94E-01	5.52E-01	3.09E-01	1.13E+00	2.13E+00
EP	kg PO4--- eq	5.10E-02	1.02E-01	5.70E-02	9.83E-02	8.41E-02	1.04E-01	5.09E-02	2.21E-01	4.51E-01
GWP	kg CO2 eq	-7.13E+02	-6.78E+02	-8.15E+02	-7.87E+02	-9.58E+02	-1.50E+03	-4.94E+02	-1.45E+03	-1.82E+03
POCP	kg NMVOC	1.71E-02	7.71E-02	2.47E-02	7.52E-02	1.09E-01	2.76E-02	1.95E-02	1.16E-01	3.40E-01
ADPM	kg Sb eq	3.12E-05	1.15E-04	3.54E-05	1.17E-04	1.12E-04	2.78E-04	2.34E-05	1.53E-04	3.21E-04
ADPE	MJ	3.81E+02	7.33E+02	4.07E+02	6.58E+02	8.71E+02	6.95E+02	4.99E+02	2.15E+03	4.80E+03
ODP	kg CFC-11 eq	6.78E-06	6.47E-06	7.08E-06	5.43E-06	8.97E-06	5.95E-06	4.19E-06	2.18E-05	4.43E-05

Annex M – Environmental impacts of Maritime pine co-products calculated by various allocation procedures

Table M. 1 - Environmental impacts of Maritime pine co-products calculated by volume allocation

Category	Unidade	SW_MP_PT	SW_Estilha	SW_Serrim	SW_Casca
GWP-t	kg CO2 eq	-7.46E+02	-7.11E+02	-7.41E+02	-7.93E+02
GWP-f	kg CO2 eq	1.29E+01	1.23E+01	1.28E+01	1.37E+01
GWP-b	kg CO2 eq	-7.59E+02	-7.24E+02	-7.54E+02	-8.07E+02
GWP-luluc	kg CO2 eq	2.01E-01	1.91E-01	1.99E-01	2.13E-01
ODP	kg CFC11 eq	2.01E-06	1.92E-06	1.99E-06	2.14E-06
AP	mol H+ eq	8.30E-02	7.91E-02	8.24E-02	8.82E-02
EP-f	kg P eq	1.12E-03	1.07E-03	1.11E-03	1.19E-03
EP-m	kg N eq	2.45E-02	2.33E-02	2.43E-02	2.60E-02
EP-t	mol N eq	2.81E-01	2.68E-01	2.79E-01	2.99E-01
POCP	kg NMVOC eq	9.80E-02	9.35E-02	9.73E-02	1.04E-01
ADP-f	MJ	1.61E+02	1.53E+02	1.60E+02	1.71E+02
ADP-m	kg Sb eq	2.02E-05	1.92E-05	2.00E-05	2.14E-05
WDP	m3 depriv.	3.31E+00	3.16E+00	3.29E+00	3.52E+00
PM	disease inc.	6.12E-07	5.84E-07	6.08E-07	6.51E-07
IRP	kBq U-235 eq	5.77E-01	5.50E-01	5.73E-01	6.13E-01
ETP-fw	CTUe	1.24E+02	1.18E+02	1.23E+02	1.32E+02
HTP-nc	CTUh	1.47E-07	1.40E-07	1.46E-07	1.56E-07
HTP-c	CTUh	3.75E-09	3.58E-09	3.73E-09	3.99E-09
SQP	Pt	1.76E+04	1.68E+04	1.75E+04	1.87E+04

Table M. 2 - Environmental impacts of Maritime pine co-products calculated bymassic allocation

Category	Unidade	SW_MP_PT	SW_Estilha	SW_Serrim	SW_Casca
GWP-t	kg CO2 eq	-1.28E+03	-8.30E+02	-4.80E+02	-5.29E+02
GWP-f	kg CO2 eq	2.22E+01	1.43E+01	8.28E+00	9.12E+00
GWP-b	kg CO2 eq	-1.31E+03	-8.45E+02	-4.89E+02	-5.38E+02
GWP-luluc	kg CO2 eq	3.46E-01	2.23E-01	1.29E-01	1.42E-01
ODP	kg CFC11 eq	3.46E-06	2.23E-06	1.29E-06	1.42E-06
AP	mol H+ eq	1.43E-01	9.23E-02	5.34E-02	5.88E-02
EP-f	kg P eq	1.93E-03	1.25E-03	7.22E-04	7.94E-04
EP-m	kg N eq	4.21E-02	2.72E-02	1.58E-02	1.73E-02
EP-t	mol N eq	4.84E-01	3.13E-01	1.81E-01	1.99E-01
POCP	kg NMVOC eq	1.69E-01	1.09E-01	6.31E-02	6.95E-02
ADP-f	MJ	2.77E+02	1.79E+02	1.04E+02	1.14E+02
ADP-m	kg Sb eq	3.47E-05	2.24E-05	1.30E-05	1.43E-05
WDP	m3 depriv.	5.70E+00	3.69E+00	2.13E+00	2.35E+00
PM	disease inc.	1.05E-06	6.81E-07	3.94E-07	4.34E-07
IRP	kBq U-235 eq	9.93E-01	6.42E-01	3.71E-01	4.09E-01
ETP-fw	CTUe	2.14E+02	1.38E+02	7.99E+01	8.79E+01
HTP-nc	CTUh	2.53E-07	1.63E-07	9.45E-08	1.04E-07
HTP-c	CTUh	6.46E-09	4.18E-09	2.42E-09	2.66E-09
SQP	Pt	3.03E+04	1.96E+04	1.13E+04	1.25E+04

Table M. 3 – Environmental impacts of Maritime pine co-products calculated by economic allocation

Category	Units	SW_MP_PT	SW_Estilha	SW_Serrim	SW_Casca
GWP-t	kg CO2 eq	-2.93E+03	-2.77E+02	-2.52E+02	-2.64E+02
GWP-f	kg CO2 eq	5.05E+01	4.78E+00	4.35E+00	4.56E+00
GWP-b	kg CO2 eq	-2.98E+03	-2.82E+02	-2.57E+02	-2.69E+02
GWP-luluc	kg CO2 eq	7.88E-01	7.46E-02	6.79E-02	7.11E-02
ODP	kg CFC11 eq	7.89E-06	7.47E-07	6.79E-07	7.12E-07
AP	mol H+ eq	3.26E-01	3.09E-02	2.81E-02	2.94E-02
EP-f	kg P eq	4.40E-03	4.17E-04	3.79E-04	3.97E-04
EP-m	kg N eq	9.61E-02	9.10E-03	8.27E-03	8.67E-03
EP-t	mol N eq	1.10E+00	1.05E-01	9.51E-02	9.97E-02
POCP	kg NMVOC eq	3.85E-01	3.65E-02	3.31E-02	3.47E-02
ADP-f	MJ	6.31E+02	5.98E+01	5.44E+01	5.70E+01
ADP-m	kg Sb eq	7.92E-05	7.50E-06	6.82E-06	7.14E-06
WDP	m3 depriv.	1.30E+01	1.23E+00	1.12E+00	1.17E+00
PM	disease inc.	2.40E-06	2.28E-07	2.07E-07	2.17E-07
IRP	kBq U-235 eq	2.27E+00	2.15E-01	1.95E-01	2.04E-01
ETP-fw	CTUe	4.87E+02	4.62E+01	4.20E+01	4.40E+01
HTP-nc	CTUh	5.76E-07	5.46E-08	4.96E-08	5.20E-08
HTP-c	CTUh	1.47E-08	1.40E-09	1.27E-09	1.33E-09
SQP	Pt	6.91E+04	6.55E+03	5.95E+03	6.24E+03

Annex N - Environmental impacts of Maritime pine strength classes calculated by the mechanical grading methodology

Table N. 1 - Environmental impacts of Maritime pine strength classes calculated by mechanical grading methodology

Category	Units	SW_MP_PT	MP_C35	MP_C24	MP_C18	MP_rejected
GWP-t	kg CO2 eq	-9.58E+02	-1.17E+03	-1.08E+03	-1.00E+03	-9.58E+02
GWP-f	kg CO2 eq	7.15E+01	8.72E+01	8.05E+01	7.49E+01	7.15E+01
GWP-b	kg CO2 eq	-1.03E+03	-1.26E+03	-1.16E+03	-1.08E+03	-1.03E+03
GWP-luluc	kg CO2 eq	1.11E+00	1.36E+00	1.26E+00	1.17E+00	1.11E+00
ODP	kg CFC11 eq	1.12E-05	1.37E-05	1.26E-05	1.17E-05	1.12E-05
AP	mol H+ eq	4.61E-01	5.63E-01	5.19E-01	4.83E-01	4.61E-01
EP-f	kg P eq	6.22E-03	7.60E-03	7.01E-03	6.52E-03	6.22E-03
EP-m	kg N eq	1.36E-01	1.66E-01	1.53E-01	1.42E-01	1.36E-01
EP-t	mol N eq	1.56E+00	1.91E+00	1.76E+00	1.64E+00	1.56E+00
POCP	kg NMVOC eq	5.44E-01	6.65E-01	6.13E-01	5.71E-01	5.44E-01
ADP-f	MJ	8.93E+02	1.09E+03	1.01E+03	9.36E+02	8.93E+02
ADP-m	kg Sb eq	1.12E-04	1.37E-04	1.26E-04	1.17E-04	1.12E-04
WDP	m3 depriv.	1.84E+01	2.25E+01	2.07E+01	1.93E+01	1.84E+01
PM	disease inc.	3.40E-06	4.15E-06	3.83E-06	3.56E-06	3.40E-06
IRP	kBq U-235 eq	3.20E+00	3.91E+00	3.61E+00	3.36E+00	3.20E+00
ETP-fw	CTUe	6.89E+02	8.42E+02	7.76E+02	7.22E+02	6.89E+02
HTP-c	CTUh	8.15E-07	9.95E-07	9.18E-07	8.54E-07	8.15E-07
HTP-nc	CTUh	2.08E-08	2.54E-08	2.34E-08	2.18E-08	2.08E-08
SQP	Pt	9.78E+04	1.19E+05	1.10E+05	1.02E+05	9.78E+04

Annex O - Environmental impacts of SW, GLT and LVL scenarios per bending strength and modulus of elasticity units

Table O. 1 - Environmental impacts of the SW, GLT and LVL scenarios per bending strength equivalent unit

Category	Unit	SW_Crypt_PT	SW_Euc_PT	SW_MP_PT	SW_Pine_DE	SW_Pine_SE	SW_Spruce_DE	SW_Spruce_SE
GWP-t	kg CO2 eq	-3.69E-01	-5.49E-01	-4.39E-01	-4.51E-01	-4.24E-01	-3.71E-01	-3.70E-01
GWP-f	kg CO2 eq	2.94E-02	2.23E-02	3.27E-02	3.30E-02	1.60E-02	3.43E-02	1.49E-02
GWP-b	kg CO2 eq	-3.98E-01	-5.71E-01	-4.72E-01	-4.85E-01	-4.40E-01	-4.06E-01	-3.86E-01
GWP-luluc	kg CO2 eq	4.24E-04	2.45E-04	5.11E-04	9.00E-04	3.78E-04	8.73E-04	2.95E-04
ODP	kg CFC11 eq	3.81E-09	2.65E-09	5.13E-09	3.46E-09	3.78E-09	4.03E-09	3.59E-09
AP	mol H+ eq	2.66E-04	2.32E-04	2.11E-04	1.73E-04	1.33E-04	1.76E-04	1.25E-04
EP-f	kg P eq	2.06E-06	1.39E-06	2.85E-06	8.37E-06	1.91E-06	8.04E-06	1.39E-06
EP-m	kg N eq	7.79E-05	7.41E-05	6.22E-05	6.25E-05	5.58E-05	6.45E-05	5.28E-05
EP-t	mol N eq	8.57E-04	8.53E-04	7.16E-04	6.90E-04	6.08E-04	7.10E-04	5.78E-04
POCP	kg NMVOC eq	2.61E-04	2.22E-04	2.49E-04	3.72E-04	2.06E-04	3.73E-04	1.78E-04
ADP-f	MJ	3.91E-01	2.66E-01	4.09E-01	4.54E-01	3.69E-01	4.71E-01	3.53E-01
ADP-m	kg Sb eq	1.74E-08	1.02E-07	5.13E-08	6.66E-08	1.79E-08	6.26E-08	1.58E-08
WDP	m3 depriv.	9.00E-03	6.98E-03	8.43E-03	5.04E-03	3.21E-03	4.27E-03	2.86E-03
PM	disease inc.	2.03E-08	1.48E-08	1.56E-09	1.60E-08	1.47E-08	1.55E-08	1.46E-08
IRP	kBq U-235 eq	1.27E-03	8.65E-04	1.47E-03	1.71E-03	6.48E-03	1.78E-03	6.40E-03
ETP-fw	CTUe	6.79E-01	8.85E-01	3.16E-01	5.94E-01	4.66E-01	5.81E-01	4.51E-01
HTP-c	CTUh	5.65E-10	5.11E-10	3.73E-10	8.93E-10	4.22E-10	8.98E-10	3.60E-10
HTP-nc	CTUh	1.02E-11	9.60E-12	9.53E-12	2.67E-11	9.50E-12	2.65E-11	7.40E-12
SQP	Pt	1.79E+01	1.00E+01	4.48E+01	5.59E+01	5.81E+01	3.53E+01	4.58E+01

Table O. 2 - Environmental impacts of the SW, GLT and LVL scenarios per modulus of elasticity equivalent unit

Category	**Unit**	**GLT**	**LVL**	**SW_Crypt_PT**	**SW_Euc_PT**	**SW_MP_PT**	**SW_Pine_DE**	**SW_Pine_SE**	**SW_Spruce_DE**	**SW_Spruce_SE**
GWP-t	kg CO2 eq	-2.91E-02	-2.68E-02	-3.51E-02	-6.23E-02	-4.72E-02	-4.03E-02	-4.28E-02	-3.45E-02	-3.60E-02
GWP-f	kg CO2 eq	8.47E-03	1.50E-02	2.80E-03	2.53E-03	3.52E-03	2.95E-03	1.62E-03	3.19E-03	1.45E-03
GWP-b	kg CO2 eq	-3.76E-02	-4.19E-02	-3.79E-02	-6.49E-02	-5.07E-02	-4.34E-02	-4.45E-02	-3.77E-02	-3.74E-02
GWP-lu-luc	kg CO2 eq	4.85E-05	1.20E-04	4.04E-05	2.78E-05	5.49E-05	8.04E-05	3.82E-05	8.12E-05	2.86E-05
ODP	kg CFC11 eq	1.25E-09	2.31E-09	3.62E-10	3.01E-10	5.51E-10	3.09E-10	3.82E-10	3.75E-10	3.48E-10
AP	mol H+ eq	6.78E-05	1.22E-04	2.53E-05	2.63E-05	2.27E-05	1.54E-05	1.35E-05	1.64E-05	1.22E-05
EP-f	kg P eq	6.17E-07	1.31E-06	1.96E-07	1.57E-07	3.06E-07	7.48E-07	1.93E-07	7.47E-07	1.35E-07
EP-m	kg N eq	2.10E-05	3.17E-05	7.41E-06	8.41E-06	6.69E-06	5.58E-06	5.64E-06	5.99E-06	5.12E-06
EP-t	mol N eq	2.48E-04	4.28E-04	8.16E-05	9.68E-05	7.69E-05	6.17E-05	6.14E-05	6.60E-05	5.61E-05
POCP	kg NMVOC eq	7.01E-05	1.23E-04	2.48E-05	2.52E-05	2.68E-05	3.33E-05	2.08E-05	3.47E-05	1.73E-05
ADP-f	MJ	1.43E-01	2.83E-01	3.72E-02	3.02E-02	4.40E-02	4.05E-02	3.73E-02	4.38E-02	3.43E-02
ADP-m	kg Sb eq	7.85E-09	1.51E-08	1.65E-09	1.15E-08	5.51E-09	5.95E-09	1.81E-09	5.82E-09	1.53E-09
WDP	m3 depriv.	3.63E-03	1.61E-02	8.56E-04	7.92E-04	9.06E-04	4.50E-04	3.24E-04	3.97E-04	2.78E-04
PM	disease inc.	3.95E-09	8.49E-09	1.94E-09	1.68E-09	1.67E-10	1.43E-09	1.49E-09	1.44E-09	1.41E-09
IRP	kBq U-235 eq	8.39E-04	1.39E-03	1.21E-04	9.83E-05	1.58E-04	1.53E-04	6.55E-04	1.65E-04	6.21E-04
ETP-fw	CTUe	3.04E-01	6.42E-01	6.47E-02	1.00E-01	3.39E-02	5.31E-02	4.71E-02	5.41E-02	4.38E-02
HTP-c	CTUh	2.46E-10	5.26E-10	5.38E-11	5.80E-11	4.01E-11	7.98E-11	4.27E-11	8.35E-11	3.50E-11
HTP-nc	CTUh	2.73E-11	1.28E-10	9.67E-13	1.09E-12	1.02E-12	2.39E-12	9.61E-13	2.47E-12	7.18E-13
SQP	Pt	7.41E+00	6.38E+00	1.70E+00	1.14E+00	4.81E+00	4.99E+00	5.87E+00	3.28E+00	4.45E+00

Annex P – Environmental impacts of various building solutions with the consideration of incineration with energy recovery at the end-of-life

Table P. 1 – Environmental impacts of various building solutions with the consideration of incineration with energy recovery at the end-of-life

Category	Unit	GLT	LVL	SW_Euc_PT	SW_MP_PT	SW_Pine_DE	SW_Pine_SE	SW_Spruce_DE	SW_Spruce_SE	IJ C24	IJ LVL
GWP-t	kg CO2 eq	3.07E+02	3.98E+02	2.36E+02	2.10E+02	3.06E+02	3.33E+02	2.97E+02	3.16E+02	2.78E+02	3.64E+02
GWP-f	kg CO2 eq	3.08E+02	3.98E+02	2.39E+02	2.12E+02	3.06E+02	3.34E+02	2.97E+02	3.16E+02	2.78E+02	3.63E+02
GWP-b	kg CO2 eq	-1.30E+00	-1.45E+00	-2.57E+00	-1.91E+00	-1.62E+00	-1.62E+00	-1.41E+00	-1.41E+00	-8.87E-01	-8.64E-01
GWP-luluc	kg CO2 eq	7.51E-01	1.34E+00	4.37E-01	3.00E-01	1.08E+00	6.25E-01	1.12E+00	5.63E-01	5.83E-01	1.22E+00
ODP	kg CFC11 eq	5.61E-05	7.39E-05	4.38E-05	4.52E-05	5.93E-05	7.00E-05	5.75E-05	6.60E-05	4.98E-05	6.42E-05
AP	mol H+ eq	2.15E+00	2.81E+00	1.24E+00	1.30E+00	1.79E+00	2.05E+00	1.78E+00	1.99E+00	1.94E+00	2.62E+00
EP-f	kg P eq	1.11E-02	1.68E-02	5.55E-03	7.51E-03	1.26E-02	6.72E-03	1.28E-02	6.37E-03	9.21E-03	1.67E-02
EP-m	kg N eq	8.11E-01	9.93E-01	4.94E-01	5.03E-01	7.21E-01	8.41E-01	7.09E-01	8.06E-01	7.33E-01	8.97E-01
EP-t	mol N eq	8.23E+00	1.07E+01	4.05E+00	4.43E+00	6.93E+00	8.24E+00	6.89E+00	7.96E+00	7.37E+00	9.73E+00
POCP	kg NMVOC eq	2.53E+00	3.24E+00	1.56E+00	1.65E+00	2.37E+00	2.58E+00	2.34E+00	2.46E+00	2.26E+00	2.93E+00
ADP-f	MJ	5.23E+03	6.94E+03	4.00E+03	4.01E+03	4.99E+03	5.55E+03	4.85E+03	5.29E+03	4.68E+03	6.41E+03
ADP-m	kg Sb eq	2.44E-04	3.04E-04	2.99E-04	2.22E-04	2.33E-04	1.92E-04	2.31E-04	1.88E-04	3.72E-04	4.54E-04
WDP	m3 depriv.	1.65E+02	2.76E+02	1.72E+02	1.51E+02	1.41E+02	1.39E+02	1.35E+02	1.33E+02	1.44E+02	2.49E+02
PM	disease inc.	5.28E-05	9.41E-05	2.56E-05	1.06E-05	3.26E-05	3.72E-05	3.23E-05	3.61E-05	2.73E-05	7.68E-05
IRP	kBq U-235 eq	2.38E+01	3.06E+01	1.61E+01	1.61E+01	2.04E+01	2.82E+01	1.98E+01	2.71E+01	1.96E+01	2.82E+01
ETP-fw	CTUe	4.80E+03	7.38E+03	-9.59E+02	2.17E+02	1.67E+03	1.84E+03	2.26E+03	2.37E+03	4.37E+03	8.46E+03
HTP-c	CTUh	1.12E-05	1.39E-05	8.13E-06	8.40E-06	1.00E-05	1.02E-05	1.01E-05	1.01E-05	1.06E-05	1.40E-05
HTP-nc	CTUh	1.30E-06	2.21E-06	1.00E-06	1.02E-06	1.07E-06	1.07E-06	1.07E-06	1.07E-06	1.17E-06	2.06E-06
SQP	Pt	9.97E+04	8.18E+04	2.30E+04	6.70E+04	7.44E+04	8.21E+04	5.92E+04	7.20E+04	8.10E+04	7.99E+04

Annex Q – Environmental impacts of various durability plans of Maritime pine products

Table Q. 1 – Environmental impacts of various durability plans of Maritime pine products

Category	Unit	Case 1	Case 2	Case 3	Case 4
GWP-t	kg CO2 eq	5.47E+02	7.82E+01	1.26E+02	3.13E+02
GWP-f	kg CO2 eq	5.46E+02	7.76E+01	1.24E+02	3.12E+02
GWP-b	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP-luluc	kg CO2 eq	7.54E-01	6.97E-01	1.37E+00	7.26E-01
ODP	kg CFC11 eq	1.00E-04	8.95E-06	1.60E-05	5.47E-05
AP	mol H+ eq	1.76E+00	1.49E+00	1.82E+00	1.63E+00
EP-f	kg P eq	1.81E-02	1.30E-02	1.68E-02	1.56E-02
EP-m	kg N eq	3.00E-01	1.96E-01	3.03E-01	2.48E-01
EP-t	mol N eq	3.34E+00	2.15E+00	3.36E+00	2.74E+00
POCP	kg NMVOC eq	1.47E+00	6.45E-01	1.04E+00	1.06E+00
ADP-f	MJ	6.11E+03	1.05E+03	1.62E+03	3.58E+03
ADP-m	kg Sb eq	1.41E-03	6.28E-03	6.38E-03	3.85E-03
WDP	m3 depriv.	7.19E+01	5.03E+01	6.59E+01	6.10E+01
PM	disease inc.	1.81E-05	5.53E-06	8.07E-06	1.18E-05
IRP	kBq U-235 eq	2.20E+01	2.98E+00	4.93E+00	1.25E+01
ETP-fw	CTUe	1.35E+04	1.51E+04	1.56E+04	1.43E+04
HTP-c	CTUh	1.42E-05	1.37E-05	1.49E-05	1.39E-05
HTP-nc	CTUh	3.12E-07	1.24E-06	2.29E-06	1.29E-06
SQP	Pt	5.91E+04	5.88E+04	1.17E+05	5.89E+04